METAMODELING – RAPID DESIGN AND EVOLUTION OF DOMAIN-SPECIFIC MODELING ENVIRONMENTS

By

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To Victoria,

A wife of noble character who can find? She is worth far more than rubies.
Proverbs 31:10 (NIV)

and

Christopher, Steven, and Michael

Like arrows in the hands of a warrior are sons born in one's youth.
Blessed is the man whose quiver is full of them!
Psalm 124:4-5 (NIV)

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure Page

LIST OF TABLES

LIST OF ABBREVIATIONS

ADL – Architectural description language

AML – Architectural meta language

API – Application programming interface

CASE – Computer-aided software and systems engineering

CBS – Computer based system

CDIF – CASE data interchange format

CM – Constraint manager

CORBA – Common object request broker architecture

DSME – Domain-specific MIPS environment

EDF – Editor description file

FM – Formal methods

GME – Graphical model editor

IDL – Interface description language

ISO – International standards organization

MCL – MultiGraph constraint language

MDF – Model description file

MDL – Modeling description language

MGA – MultiGraph Architecture

MGK – MultiGraph kernel

MIC – Model integrated computing

MIPS – Model integrated program synthesis

MODL – Meta-object definition language

MOF – Meta object facility

OCL – Object constraint language

OMT – Object modeling technique

POSIX – Portable operating system interface

SDAI – Standard data access interface

STEP – Standard for product data exchange

UML – Unified modeling language

VHDL – VHSIC hardware description language

VHSIC – Very high speed integrated circuit

CHAPTER I

INTRODUCTION

Large computer-based systems (CBSs), where functional, performance, and reliability requirements demand the tight integration of physical processes and information processing, are among the most significant technological developments of the past 20 years [1]. CBSs operate in ever-changing environments, and throughout a CBS system's life cycle, changes in mission requirements, personnel, hardware, support systems, etc., all drive changes to the CBS. Rapid reconfiguration via software has long been seen as a potential means to effect rapid change in such systems. Examples of such environments include process control and monitoring; real-time diagnostics and analysis; information distribution and management; surety of high consequence, high assurance systems; and fault detection, isolation, and recovery.

Due to the extremely complex nature of large-scale, mission-critical systems, software modification involves a large amount of risk. The magnitude of this risk is proportional to the size of the system, not to the size of the change. Small modifications in one area can cause large and unforeseen changes in others. Because such risk is always present, it must be managed. To effectively manage such risk, the entire system must be *designed* to evolve. Key factors in this evolution are:

- **Requirements capture**: A method to state the system's requirements and design in concise and unambiguous terms.

- **Program synthesis**: The ability to automatically transform requirements and design information into application software.
- **Application evolution**: A method to safely and efficiently evolve the software over time as application requirements change.
- **Design environment evolution**: A method to ensure the design environment can correctly model domain-specific systems as domain requirements change.

An emerging technology that enables such evolution is model integrated computing (MIC). MIC allows designers to create *models* of domain-specific systems, validate these models, and perform various computational transformations on the models.

One approach to MIC is model-integrated program synthesis (MIPS). In MIPS, models are created that capture various aspects of a domain-specific system's desired behavior. Model *interpreters* are used to translate these models for use in the system's execution environment, either as stand-alone applications or in conjunction with code libraries and some form of middleware (e.g. CORBA, the MultiGraph kernel (MGK), POSIX, etc.) When changes in the overall system require new application programs, the models are updated to reflect these changes, and the applications are regenerated automatically from the models.

The MultiGraph Architecture (MGA), under development at Vanderbilt University, is a toolset for creating domain-specific MIPS environments. Although the MGA provides a means for quickly and accurately evolving domain-specific applications, such capability is generally not enough to keep pace with large changes in systems requirements. Throughout the lifetime of a system, particularly a large-scale system, requirements often change in ways that force the entire design environment to change.

For example, if a domain-specific MIPS environment (DSME) exists for modeling a chemical plant and generating executable code for use on the plant's monitoring and analysis computers, what happens when new equipment is later added to the plant – equipment that was not in use or was unheard of at the time the DSME was created? In all likelihood, the existing DSME would not be able to model new configurations of the plant. In a case such as this, the entire DSME would have to be rebuilt so that new equipment could be incorporated into existing and future plant models.

Clearly, these DSMEs must be updated as changes in the domain arise. Currently, DSMEs are handcrafted, and rebuilding a DSME can be a long and costly process. What is needed is a way to *automatically generate the DSME*. One approach is to model the DSME itself – to "model the modeling environment" in a manner similar to modeling a particular domain-specific application. (In fact, a DSME *is* a domain-specific application, where the domain is the set of all possible MIPS environments). Just as domain-specific models are used to generate domain-specific applications, by adding a *metaprogramming interface* to a MIPS environment, the MIPS environment can be used to generate various DSMEs. Such a MIPS environment is called a *metamodeling environment*. Because models created using a metamodeling environment describe other modeling systems, they are called *metamodels*. Metamodels are formalized descriptions of the objects, relationships, and behavior required in a particular DSME. It can be seen that this approach to DSME design and evolution is similar to that of evolving domain-specific applications using DSMEs – just "up one level" in the design hierarchy.

The MGA has been in use for almost 10 years, and has provided the tools necessary to create a wide variety of DSMEs. Currently, however, the MGA supports only a rudimentary metaprogrammable interface. Therefore, my thesis is:

It is possible to specify, synthesize, and evolve domain-specific modeling environments by designing and incorporating a complete meta-programming layer into the MGA, thereby reducing the risk of large-scale computer-based system development.

This dissertation presents the concepts behind, and a methodology for, creating such a metaprogramming layer and incorporating it into the MGA. The background section discusses metamodeling concepts and challenges, develops a taxonomy of metamodeling language criteria, and presents the results of a metamodeling languages literature review, including an analysis of each language based on the previously developed criteria. The background section concludes by presenting preliminary metamodeling research performed in preparation for this dissertation.

Next the various modeling environment resources are discussed, such as the facilities for creating, visualizing, and composing metamodels. Constraint management and persistent storage are also discussed, and a general strategy is developed for mapping UML-based metamodeling specifications to the MultiGraph graphical modeling environment. The complete metamodeling process is presented, and the prototype UML/GME metamodeling environment is presented and discussed.

Following this discussion, a case study is conducted to demonstrate how the metamodeling tool is used to specify and synthesize various domain-specific modeling

environments. The results of the case study are analyzed to determine the capabilities and usability of the metamodeling environment, as well as to identify any limitations and restrictions imposed on the metamodeler by the system. Finally, recommendations for future enhancements to the UML/GME metamodeling system are presented.

CHAPTER II

BACKGROUND

This section provides the proper context for the UML/GME metamodeling discussion that follows in Chapter III. A more detailed review and discussion of modeling, model-integrated computing, and model-integrated program synthesis is provided in Appendix A.

Model Integrated Program Synthesis

Modeling is the process of creating an abstract representation of a system, and as such, becomes a key strategy in the system design process. The artifacts of the modeling process are *models* – abstractions of the original system. The most important feature of a model is its ability to reduce the complexity of a design. To aid designers in creating models of hardware and software systems, various modeling languages and systems have been created. For such modeling systems to be successful, they must be specific enough to enable designers to represent the key elements of various designs, without unduly constraining the designer, while remaining general enough to allow a fairly wide variety of models to be created.

Modeling languages exist for many domains, serving many purposes. Some modeling languages are more suited to the task of hardware and software modeling that others. This dissertation concentrates on languages designed to model CBSs. The functional, performance, and reliability requirements of CBSs demand tight integration of physical systems with information systems [2]. When modeling such systems, it is

important that these requirements be captured in a *unified* set of models. Only with a unified model set can each aspect of the system's overall behavior (i.e. the functional, performance, and reliability aspects) be examined as a "separate but integrated" part of the overall CBS. As discussed in Appendix A, there are several criteria for choosing a CBS modeling language. These include:

- the ability to model general engineering entities and relationships,
- acceptance of the language as a standard,
- support for a variety of modeling techniques (e.g. state-charts, petri-nets, etc.)
- model composition and reuse capability,
- modeling language extensibility,
- support for an automated design environment,
- the ability to conduct formal analysis and simulation of models,
- the ability to assign semantic meaning to models,
- transformation of structural and behavioral models into executable models, and
- metalanguage support.

Of particular importance is support for a metalanguage – the basis of metamodeling.

Model-integrated computing (MIC) is a methodology for synthesizing applications from domain-specific models. MIC allows designers to create multi-aspect models of domain-specific systems, validate these models, and perform various computational transformations on the models. One approach to MIC is model-integrated program synthesis (MIPS).

MIPS is a method that allows experts in a particular domain to create integrated sets of multi-aspect models representing all or part of various domain-specific systems. These models can then be transformed for use in the system's execution environment, either as stand-alone applications, or in conjunction with code libraries and some form of middleware (e.g. CORBA, the MultiGraph kernel (MGK), POSIX, etc.) As application requirements change over time, the models are updated and new applications are synthesized, thus allowing for safe and efficient *application evolution*.

A MIPS environment operates according to a *modeling paradigm* – a set of requirements that governs how *any* system in a particular domain is to be modeled. These modeling requirements specify the types of entities and relationships that can be modeled; how best to model them; entity and/or relationship attributes; the number and types of views or aspects necessary to logically and efficiently partition the design space; how semantic information to is to be captured by, and later extracted from, the models; any analysis requirements; and, in the case of executable models, run-time requirements.

Once a modeling paradigm has been established, the MIPS environment itself can be built. A MIPS environment consists of three main components: (1) a domain-aware *model builder* used to create and modify models of domain-specific systems, (2) the *models* themselves, and (3) one or more *model interpreters* used to extract and translate semantic knowledge from the models. See Appendix A for a detailed description of each of these components.

Metamodeling Concepts

More and more, the prefix *meta* is being attached to words that describe various modeling and data representation activities. For example, a literature search on the

keyword "metamodel" will yield many references to "meta" methods and terms such as *metamodeling*, *metadata*, *metarelation*, *metaassociation*, *metaattribute*, *metaclass*, *metaobject*, *metaCASE*, etc. Unfortunately, the term “meta” is not applied consistently, causing considerable confusion among researchers. Therefore, in the context of this dissertation, the following definitions apply:

- **Model**: An abstract representation of a CBS.
- **Modeling Environment**: A system, based on a modeling paradigm, for creating, analyzing, and translating domain-specific models.
- **Metamodel**: A model that formally defines the syntax and semantics of a particular domain-specific modeling environment.
- **Metamodeling Environment**: A tool-based framework for creating, validating, and translating metamodels.
- **Meta-metamodel**: A model that formally defines the syntax and semantics of a given metamodeling environment.

To better compare and contrast metamodeling approaches and methodologies, a taxonomy of metamodeling language characteristics is necessary. Such a taxonomy is best developed by examining fundamental metamodeling concepts.

In a very real sense, modeling and metamodeling are identical activities – the difference being one of interpretation. Models are abstract representations of real-world systems or processes. When the process being modeled is *the process of creating other models*, the modeling activity is correctly termed metamodeling. Therefore, concepts that apply to modeling also apply to metamodeling. This logic can be extended to the process

of meta-metamodeling, too. However, because of the goals of modeling, metamodeling, and meta-metamodeling are quite different, a four-layer conceptual framework for metamodeling has been established and is in general use by the metamodeling community. The following table, taken from [3], describes each layer:

Table 1: Four-layer metamodeling architecture

Layer	Description
Meta-metamodel	The infrastructure for a metamodeling architecture. Defines the language for describing metamodels.
Metamodel	An instance of a meta-metamodel. Defines the language for specifying a model.
Model	An instance of a metamodel. Defines a language to describe an information domain.
User objects	An instance of a model. Defines a specific information domain.

This four-layer architecture creates an infrastructure for defining modeling, metamodeling, and meta-metamodeling languages and activities, and provides a basis for future metamodeling language extensions. The architecture also provides a framework for exchanging metamodels among different metamodeling environments – critical for tool interoperability, since such interoperability depends on a precise specification of the structure of the language [3].

Modeling Syntax, Semantics, and Presentation

To properly capture the *syntax* of a modeling language, a metamodel must describe all entities and relationships that may exist in the target language. In the case of

a multi-aspect modeling language, the metamodel must clearly define a partitioning of these entities and relationships across all aspects of the modeling language. This is especially important in the case of graphical modeling languages. As discussed in [3], when specifying graphical modeling languages, an *abstract syntax* – a language syntax devoid of implementation details – is first specified. Then a *concrete syntax* is defined as a mapping of the graphical notation onto the abstract syntax. In a graphical metamodel, the syntax is modeled as a collection of modeling object types, along with the relationships allowed between those object types and any attributes associated with the objects.

In addition to specifying the syntax of modeling language, *semantics* must also be specified in a metamodel. For example, consider a DSME for embedded processor modeling. A metamodel describing such an environment would likely include *processor* and *sensor* entities, and a *connectedTo* relationship specifying how sensors are related to processors. Furthermore, the *number* of individual processors and sensors that participate in the connectedTo relationship must also be specified, so the metamodel would need a multiplicity specification for the connectedTo relationship. Depending on the particular types of processors and sensors, such a metamodel might specify that one sensor can be connected to at most three processors, or that one processor can be connected to no more than five sensors.

It is necessary to distinguish among two types of semantics – *static* and *dynamic*. Static semantics refer to the well-formedness of constructs in the modeled language, and are specified as invariant conditions that must hold for any model created using the modeling language. Dynamic semantics, however, refer to the interpretation of a given

set of modeling constructs *in the context of the model instances themselves*. Only the static semantics may be specified in a metamodel, since the metamodel has no way of knowing *a priori* what meaning to associate with particular instances (i.e. particular models) created using the language. Distinguishing between static and dynamic semantics is best illustrated by an example.

Consider a MIPS environment used to model the behavior of real-time scheduling systems. A metamodel description of such a MIPS environment would necessarily define objects and relationships such as *tasks*, *events*, and *schedules*. The static semantics expressed in the metamodel would include constraints that must be maintained to ensure a given model is valid. Scheduler models that violate any of these constraints are, by definition, invalid models. Some possible constraints, stated using standard English, might be:

- "Task duration must be specified"
- "Schedules can hold a maximum of 10 tasks"

Such constraints represent the static semantics of the modeling language, and can be defined in the metamodel. However, the following constraints represent dynamic semantics, and as such, cannot be represented as metamodel constraints:

- "All tasks must meet their execution deadlines"
- "Scheduling queues must never overflow"

The metamodel can define what it means for a task to have a duration associated with it, and can specify that such "meaning" must be satisfied in any model that includes

tasks. If the modeler fails to provide a value for task duration, the model is considered invalid. However, the metamodel cannot specify the enforcement of a specification concerning task schedulability, since schedulability is a function of, among other things, certain run-time factors – factors that the metamodel has no *a priori* knowledge of.

Another consideration in any metamodeling language is the form of these invariant constraint statements. Constraints must be stated in such a way as to be precise and analyzable, so that before any modeling language or modeling environment is synthesized from a metamodel, it can be shown (i.e. *proved*) that the metamodel itself does, in fact, properly specify a set of constraints (constraints that properly define the static semantics of the modeling language in question). Therefore, the static semantics should be specified in a mathematical language. An ideal candidate is any first- or higher-order predicate calculus, since the invariants can take the form of Boolean expressions that must be satisfied by any model created using the target modeling language. Such expressions can be tested using a proof checker before the metamodel is used to generate a modeling language.

In a metamodel, it is important to separate form from function when describing the target modeling language. Language implementation details (i.e. the "form"), while necessary to implement the target MIPS environment, need not, and arguably *should not*, be included in a metamodel. Implementation details do not add meaning to the simple and precise syntactic and semantic modeling language specifications (the "function"), and will, oftentimes, obscure the specification and make metamodel interpretation more difficult.

As stated earlier, making modeling (and metamodeling) tools interoperable requires that metamodels be exchanged among various metamodeling tool suites. This requires that the structure of any language – its syntax and semantics – be precisely specified by the metamodel, even if other aspects, such as implementation details, are not. Therefore, the metamodeling environment must be able to accept metamodels specified in a variety of metalanguages, or those metalanguages must be translatable to a metalanguage that the metamodeling environment understands. This again underscores the need to separate the implementation details from the language specification itself.

Model Composition, Validation, and Translation

The field of engineering contains many domains, such as process control, digital signal processing, and information management. While each domain deals with inherently different notions, certain modeling concepts can be applied to many, if not all, engineering domains. For example, hierarchy is used in many engineering disciplines to represent concepts such as information hiding, abstraction, and object inheritance.

Another example is the concept of *module interconnection* [4], where clearly defined interfaces are specified between modules, and modules connect to one another across these interfaces. Modules may contain one or more *ports* (i.e. specific connection points) used when making connections to other modules. There are specific rules governing the use of these ports, such as:

- Input ports can connect to output ports
- Output ports can connect to input ports
- Output ports can not connect to other output ports

These module interconnection rules represent constraints that apply whenever module interconnection is used as a means of modeling component interaction. They apply whenever module interconnection is used, regardless of which particular engineering domain the system being modeled belongs to.

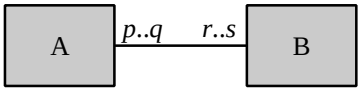
The goal is to represent such modeling concepts abstractly as *generalized model composition constraints*, and place these representations in a repository or library. The metamodeler can then access these library objects and *compose* a metamodel by combining the constraints in ways dictated by the modeling paradigm. Such an approach allows quick and accurate construction of metamodels – assuming, of course, that each constraint has been validated *a priori*, and that the act of combining or composing constraints does not negate the individual validations (or that re-validation of the composed specification can be easily accomplished).

Table 2: General model composition constraints

Constraint Name	Constraint Description
Module Interconnect	Provides rules for connecting objects together and defining interfaces. Used to describe relationships among objects.
Aspects	Enables multiple views of a model. Used to allow models to be constructed and viewed from different "viewpoints."
Hierarchy	Describes the allowed encapsulation and hierarchical behavior of model objects. Used to represent information hiding.
Object Association	Binary and n-ary associations among modeling objects. Used to constrain the types and multiplicity of connections between objects.
Specialization	Describes inheritance rules. Used to indicate object refinement.

Table 2 describes several general model composition constraints. Not all domains need every constraint available in the library. For example, a simple process control modeling language may not require hierarchical behavior. For this reason, when creating domain-specific modeling languages, concepts specific to the domain must be known *a priori* and must be used to guide the selection of constraints from the library.

Because of the general nature of the constraints listed in Table 2, they are "family-specific" (e.g. engineering-specific) but not domain-specific. Before they can be used in a domain-specific metamodel, they must be tailored for the domain. One approach is to *parameterize* the constraints. As an example, consider the constraint shown in Figure 1. It represents a general constraint on object association. The constraint is shown both graphically and textually.




```
ObjAssociation(A, p, q, B, r, s) {
  // f is a parameterized, invariant
  // Boolean expression representing
  // object association.
  return f(A,p,q,B,r,s);
}
```

Figure 1: General object association constraint (shown graphically and textually)

This constraint specifies that, in general, an object of type *A* can be associated with between *r* and *s* objects, inclusive, of type *B*, and objects of type *B* can be associated with between *p* and *q* objects, inclusive, of type *A*. Of course, a particular engineering domain will have specific names for these object types and specific values for the association multiplicities.

Now consider an aircraft in-flight safety system modeling environment, where between three and six engine temperature sensors can be associated with a single fire suppression system actuator. The general object association constraint can be customized for this particular domain as follows:

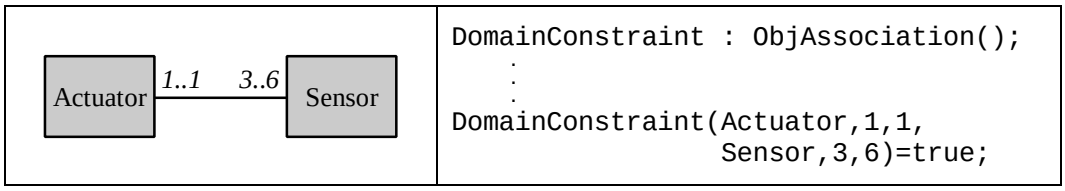


Figure 2: Domain-specific object association constraint (shown graphically and textually)

By customizing the general model composition constraints, the metamodeler injects domain-specific concepts into the metamodel. As shown in Figure 2, this can be done efficiently by creating an instance of the general constraint, and passing domain-specific parameters to it, thus "customizing" the constraint for the domain. This allows the general constraint to be used to represent a concept specific to the particular domain in question.

However, tailoring general modeling constraints in this manner is still not enough to fully specify a modeling language. There must be a mechanism for the metamodeler to include *domain-specific constraints* – constraints that, even in their general form, pertain only to the domain being modeled. These constraints can take the form of additional invariant Boolean expressions written directly into the metamodel. Only by customizing the generalized modeling constraints with concepts specific to the domain, and supplementing these constraints with *ad hoc* domain-specific constraints, can the metamodel fully specify a domain-specific modeling language. Figure 3 shows how

metamodels can be composed by combining the various model composition constraints and concepts just discussed.

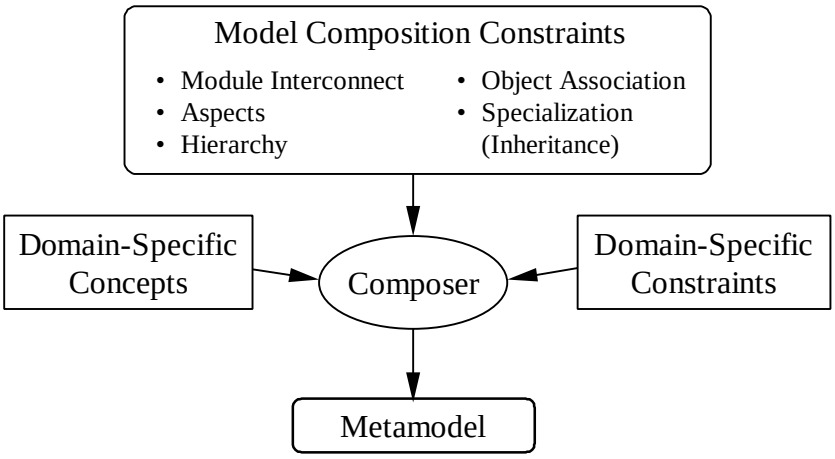


Figure 3: Metamodel composition

Once the syntactic and semantic specifications for a modeling language are composed into a metamodel, a complete language specification exists, albeit still abstract. Additional specifications regarding how the modeling environment presents the language's entities and relationships to the modeler must be made. In other words, the language specification is not a specification *for an entire modeling environment*. It can be argued that presentation specifications are merely additional syntactic specifications. However, in general it is desirable to keep the presentation specifications separate from the syntactic entity and relationship specifications discussed above.

Similarly, since a general modeling environment should include facilities for extracting information from instance models created using the environment, a set of model interpretation specifications should be included when specifying a complete DSME. Such interpreter specifications are a form of semantic specification, but as with

the presentation specifications, it is better to develop and maintain interpreter specifications separately from the semantic specifications already discussed.

In summary, four types of specifications – syntactic, presentation, semantic, and interpretation – must exist in a metamodel, and are necessary and sufficient to completely specify a domain specific modeling environment. For the remainder of this dissertation, the term metamodel will refer to this "complete" definition of a metamodel.

Once a metamodel has been created, it is used to synthesize and/or configure various components in the DSME. Because the metamodel contains syntactic, semantic, presentation, and interpreter specifications, most, if not all, of the DSME can be directly synthesized from the metamodel.

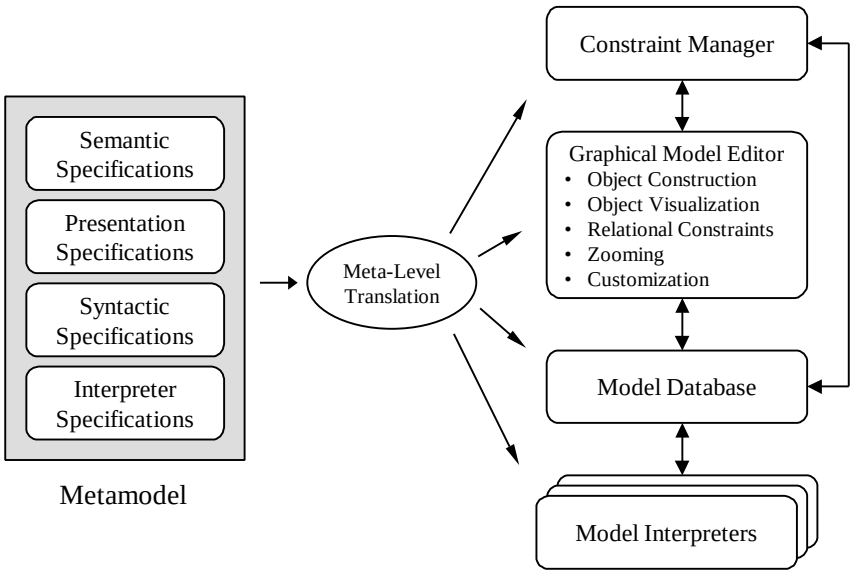


Figure 4: Metamodel translation

Figure 4 shows that by performing a meta-level translation, the metamodel specification on the left can be used to generate the DSME on the right. The semantic

specifications in the metamodel are used by the DSME constraint manager to verify that models created using the DSME are legal – i.e. they don't violate any of the semantic constraints specified in the metamodel.

The presentation and syntactic specifications are used to configure the DSME's graphical model editor. This includes managing how various aspects of the models are presented, how objects are created, controlling the type and multiplicity of object associations, as well as allowing storage and retrieval of models from persistent storage. Information in the metamodel is also used to generate the schema for the model database and the database interface code for the constraint manager and the graphical model builder.

Finally, as discussed in [5], portions of the model interpreters can also be synthesized from the interpreter specifications contained in the metamodel.

Constraint Management

The activity of modeling is essentially choosing a particular model from an infinite set of possible models. By limiting the types of modeling objects and relationships allowed in the models, the set of possible models can be greatly reduced. (Of course, the set is still infinite!) As discussed in the previous section, these limitations represent the static semantics of a modeling paradigm, and, as such, appear as domain-specific modeling constraints in the metamodel. Remember, such constraints can only be enforced in the presence of actual domain-specific models – i.e. model *instances* created using the modeling language specified by the metamodel. Enforcing these constraints is done by a *constraint manager*. The constraint manager is part of the domain-specific

modeling environment. It provides various queues to the modeler according to the static semantics described in the metamodel.

As an example of constraint management, consider an audio signal processing modeling paradigm. The metamodel specifies the following types of objects: microphones, preamps, power amps, and loudspeakers. Microphones contain one output port, preamps and power amps each contain a single input and output port, and a loudspeaker contains a single input port. The metamodel also specifies the following relationships among the types: a microphone's output port may be connected to the input ports of any number of preamps, a preamp output port may connect to any number of power amp input ports, and a power amp output port may connect to one or more loudspeaker input ports. Such syntactic model construction rules can be easily enforced in the graphical model editor – the graphical editor simply won't allow any objects or relationships not specified in the metamodel to exist. However, suppose a domain-specific constraint is included in the metamodel stating that the output of every power amp must be connected to *something* (a very important real-world consideration). Although such a constraint can easily be stated in the metamodel (for example, by including an invariant expression stating that the size of the set of objects connected to the output of any power amp be greater than zero), such a constraint can only be checked once a specific model exists. In other words, the graphical model editor can *prevent* certain editing actions, but cannot *guarantee* certain editing actions. Of course, the constraint manager can't guarantee certain editing actions either, but it can indicate that, at a given point in time, a certain model does not satisfy a particular constraint.

As explained above, the constraint manager operates on model instances. Such a "constraint enforcement mechanism" should not be confused with the formal metamodel validation that is performed *before* any domain-specific modeling environment is synthesized from the metamodel. Metamodel validation is used to ensure that any modeling environment created from the metamodel specifications will generate valid models in the domain (i.e. that the modeling language specification is *consistent*). For reasons of speed, accuracy, and completeness, the metamodeling language should allow for machine-aided validation of metamodels. This is only possible when the metamodel specifications are expressed using a formal language. One possibility would be a metamodeling language based on Boolean predicate calculus. In the case of graphical modeling languages, such a calculus can take the form of a supplementary set of constraint expressions written in an appropriate Boolean expression language. In this case, care must be taken to ensure the names of object types and relationships appear correctly in the Boolean expressions. This can be handled as an implementation detail.

Literature Review of Metamodeling Languages

As mentioned in the introduction, the MGA has only a rudimentary metaprogramming interface, inadequate for several reasons. First, a declarative language is used for defining modeling paradigms. This simple metalanguage does not support a rigorous and concise specification of complex modeling semantics. Second, the language does not support machine-aided validation of the modeling environment definition. Finally, there is no support for the formal specification of model interpreter semantics or the semantics of any execution environments, making any verification and validation of interpreters and execution environments difficult at best [5]. Since the goal is to use the

MGA as a metamodeling environment, a new, more complete metamodeling language must be implemented in the MGA.

What follows is a discussion of several currently available metamodeling languages and/or metamodeling environments. These will be explained and compared using the criteria developed in the previous Metamodeling Concepts section. Those criteria are summarized below:

- Support for the four-layer metamodeling architecture.
- Ability to model both the abstract syntax and static semantics of a modeling language.
- Ability to separate modeling language syntax and semantic specifications (the "function") from implementation details (the "form").
- Ability to compose metamodels from pre-specified, generalized modeling constraints, supplemented with necessary domain-specific concepts and constraints.
- Ability to specify static semantics as a set of provably correct invariant expressions (i.e. *constraint* expressions).
- Ability to validate the consistency of metamodel using machine-aided methods such as theorem provers or proof checkers.
- Support for metamodeling tool interoperability by allowing metamodels to be translated to and from other metamodeling languages.

Aesop and Armani

Carnegie Mellon's Architecture Based Languages and Environments project group explores the formal basis for Software Architecture and builds tools for practicing software architects. One such tool, Aesop [6], is a toolkit for producing customized

Software Architecture design and analysis environments. While there is no well-accepted definition for Software Architecture, it is generally recognized that a system's architectural design (i.e. its Software Architecture) is concerned with describing its gross decomposition into computational elements and the interactions among those elements [7][8]. This represents a rather high level of design abstraction, one that is removed from the details of algorithm design. Such an approach concerns itself with component composition, control structures, system evolution, and the ability to choose from among design alternatives. Because software engineers tend to reuse established architectural organization principles (e.g. client-server, producer-consumer, pipe-and-filter, etc.), they tend to apply certain reference models and patterns of solution to particular categories of problems. A set of generalized, category-specific solutions is referred to as an *architectural style*.

Aesop allows designers to define architectural styles and apply them when modeling various software architectures. Each style-specific architectural development environment created by Aesop supports:

- selection of design element types (i.e. style-specific components and connectors) as specified by the style,
- design checking to ensure compliance with the particular style's topological constraints,
- an optional statement of element semantics (using a text-based language of the modeler's choice),
- an interface that gives external tools access to the architectural descriptions (for manipulation and analysis of the descriptions),

- various visualizations of the architectural designs, and
- a graphical editor for creating the designs themselves.

The architectural design elements in Aesop are similar to those found in ACME [9][10], an Architectural Description Language (ADL) used to describe software systems. ACME and Aesop both use *components* and *connectors* as basic architectural elements. Components and connectors both have *interfaces*. Component interfaces are called *ports*, and connector interfaces are called *roles*. Components and connectors are interconnected in a straight forward manner – component ports attach to connector roles, and connector roles attach to component ports – to form representations of software architectures. Both ACME and Aesop use aggregations of components and connectors to form representations of larger, more complex software systems. ACME terms such aggregations *systems*, while Aesop terms them *configurations*. Systems and configurations also support interconnection interfaces.

As Monroe states in [11], experience has shown Aesop to be useful for capturing broad design expertise in the form of architectural styles, and allows the use of these styles in the design various software systems. However, Aesop has four major drawbacks. First, the architectural styles created with Aesop are inflexible and non-extensible. Style semantics are not easily modified or updated by Aesop users (the given style's semantics are captured as C++ class methods and data members). Also, because a style embodies many interrelated design notions, it is difficult to separate and reuse portions of a style. Modifying one part of a style can severely impact the behavior and usability of the rest of the style. Second, the ability to express design expertise is limited. Style specifications define invariant properties that apply to every system created using a

particular style, and unless a software design principle can be specified using invariant specifications, it is difficult or impossible to represent as a style. For example, it is difficult to represent design heuristics using Aesop. Third, a designer has little or no control over how the various "rules" of a style are enforced, and the designer cannot add *ad hoc* design constraints while using Aesop – the entire style must be modified, resulting in a new style that applies to all designs created using that style. Related to this is the fourth drawback: Aesop allows very little "experimentation" with design alternatives, since no mechanism exists for making temporary extensions or modifications to the conceptual framework surrounding the individual designs.

Because of these limitations, Monroe has begun work on the Armani system [11]. Armani is an ACME-based tool for creating software architecture designs. Armani uses the familiar ACME notions of *components*, *connectors*, and the Aesop *configuration*, but redefines the notion of an architectural style as "a collection of modular, first-class, design rule and design vocabulary specifications." Armani makes these first-class design rule objects accessible to the end user of the system (i.e. the software architect). By giving the architect the ability to create, modify, and combine these design rules *while using the system to create specific software architectural designs*, the architect takes on the role of style specifier as well as architectural system designer. Armani gives an architect the freedom to specify new rules, to define various exception handing policies for those rules, and to declare a rule's scope, deciding whether the rule should apply only to a particular design entity, a group of entities, or to an entire style. Armani also allows the system user to temporarily disable design rules during various stages of the design process.

The Armani concept of an architectural style can be thought of as a metamodel, and so Armani is an environment for creating metamodels, allowing the modeling environment designer (i.e. the architectural style designer) to specify syntactic as well as semantic aspects of a modeling language. And although Armani is implemented in an integrated design environment, the language supports a clean separation of syntax and semantics. Semantic definitions can be extracted for use with a proof checking system.

While Armani represents significant improvements over Aesop, Armani has its drawbacks. Although the Armani notion of an architectural style has been improved, it is still rather inflexible. Styles can be modified, but only using predefined notions of software design – notions that must be implemented "under the hood" of Armani. Related to this is the lack of support for the four-layer metamodeling architecture. No capability exists for Armani to define or model itself (i.e. no meta-metamodel description of Armani can be defined from within Armani itself). Model migration is very much an open issue, since the Armani design environment is so highly coupled to the software architecture models themselves, but the Armani language appears able to support model translation. Finally, and perhaps most importantly, Armani, like its predecessor Aesop, is a tool designed "from the ground up" for *software architecture* design. It does not have sufficient breadth for use in defining domain-specific modeling languages – a necessary requirement for any metamodeling language used with the MGA.

Architecture Meta-Language

Architecture Meta-Language (AML) is a recently proposed language for specifying the semantics of architecture description languages (ADLs) [12]. AML provides the ADL designer (i.e. the *metamodeler*) with primitive set of constructs,

namely *elements*, *kinds*, and *relationships*, which can be used to define the structure of an ADL. Also, the metamodeler can constrain the dynamic evolution of the target ADL through the use of temporal predicate logic statements. AML is an extension of ACME.

Elements are the basic entity construct in AML. Elements contain *parts*, which may include other elements. AML kinds operate as type specifications. Relationships are named, parameterized, first-class design entities in AML, and are used to specify syntactic and semantic relationships among elements. Elements, kinds, and relationships may all contain *assumptions*, written in AML's predicate language (see below), and may be used in ADL specification expressions.

AML supports the dynamic evolution of an ADL in two ways. First, parts contained in an element can be specified by using two types of element specifications – *closed* or *open* specifications. Closed specifications state explicitly what parts are contained within an element. Most ADLs support this closed style of specification, where an explicit description of object types and multiplicities is given. An open specification also allows for explicit enumeration of an element's parts, but also allows for the future inclusion of parts not identified in the original specification.

Second, dynamic evolution is supported by *assumptions* and *derivations* written in AML's predicate-based constraint language. The language supports traditional Boolean predicate expressions involving the three constructs (elements, kinds, and relationships) present in AML. See [12] for a preliminary specification of this language. Assumptions are equivalent to *axioms* in predicate calculus, and derivations are equivalent to *theorems*. Assumptions must be valid apart from any instances – they must hold universally for the specified ADL, while derivations are provable from assumptions, but only within the

context of instances. Therefore, any proof-checking system that supports an AML design environment must be able to check the assumptions before any actual designs are created (i.e. at metamodeling time). Of course, there must also be theorem-proving support for ensuring that derived specifications hold when the ADL is used to specify (i.e. model) a particular architecture.

Because AML is still in the early stages of development, no AML standard currently exists (in fact, many portions of [12] are still incomplete). However, as proposed, AML has the promise of becoming a solid metamodeling language. AML, like Armani, was designed to specify ADLs, but AML has taken a more general approach, allowing greater flexibility and adaptability on the part of language designers to extend AML for use in domains outside of software architecture. While not specifically designed to support the four-layer metamodeling architecture, AML clearly supports metamodeling, and, upon initial inspection, appears able to specify itself. It cleanly separates syntactic specification from semantic specification. The language is implementation independent, making no attempt to define an implementation environment. The AML predicate language is, to quote Wile, "subject to redesign," but appears to contain the necessary elements for specifying the static semantics of an ADL. No mention is made in [12] of a theorem prover capable of supporting AML, but because AML depends heavily on valid predicate expressions to specify ADL semantics and dynamic evolution, this shortcoming will likely be worked out in the near future. (Note: such a dependence on predicate logic will require a greater-than-average understanding of formal specification techniques on the part of any ADL specifier). AML is a highly structured language, and as such, should support translation and migration of language

specifications, thus supporting metamodeling tool interoperability. At this point, it is unclear how one might compose AML specifications from predefined sub-specifications, however.

As stated earlier, AML is still in its infancy, but a few attempts have been made to model real-world languages. One such effort reported by Wile is to model the C2 architectural description language. Wile compares a UML model of C2 with an AML model. He concludes that the AML representation is more concise, in part because AML was designed to capture exactly the types of constructs in C2 (as well as other ADLs), and because AML's *attach* construct is polymorphic, allowing a single, general attachment specification to be reused throughout the specification.

CASE Data Interchange Format

The Computer Aided Software and Systems Engineering (CASE) Data Interchange Format (CDIF) is a family of standards that define:

- a framework for modeling data and metadata (i.e. data that describe other data),
- metamodeling concepts, including an integrated metamodel supporting many modeling techniques and approaches,
- transfer formats to allow exchange of metadata between applications, and
- textual and graphical representations for syntactic and semantic modeling information.

CDIF represents an organic, international standard that defines a single, unified architecture for representing modeling and metamodeling data, exchanging that data

between various modeling tools and data repositories, and providing standardized interfaces for those tools [13]. CDIF allows tool builders to provide a single import/export interface for exchanging data with any other CDIF-compliant modeling tool. CDIF defines an integrated metamodel (i.e. a common, well-defined description of what the models mean to the tools exporting them) as well as standardized views or aspects for use by presentation tools. Data is defined once, and reused as necessary across various aspects. Exporters are expected to provide as much data as possible (within the scope of the transfer), and importers can reject any data that they cannot use. Although exporters are allowed to *extend* the CDIF Integrated Metamodel (i.e. to define a localized, *ad hoc* "standard" of exchange), they are encouraged to restrict the practice to cover only concepts not currently covered in one or more of the CDIF Subject Areas (see below). Also, the exporter must follow the methods specified in the CDIF Framework for Modeling and Extensibility [14] for notifying importers that such extensions exist, how those extensions are specified, and what semantics are associated with the extensions.

CDIF is designed from the ground up to support the general, four-layer metamodel architecture used by many metamodeling languages, and can be used to define itself. CDIF specifies syntax and semantics separately, allowing any CDIF model to be exchanged using any of the available transfer formats, such as CDIF's clear text format, CDIF's SYNTAX.1, or OMG's Common Object Request Broker Architecture (CORBA) [15] standard. These transfer formats support efficient transfer of data in accordance with the various "Subject Areas" defined by CDIF. Subject Areas are specifications for storage and transfer of data peculiar to particular modeling techniques. For example, there are Subject Areas covering State-Event modeling, Relational

Database modeling, Object-Oriented Analysis and Design modeling, Data Flow modeling, and Business Process modeling, to name a few.

There are two models of information in CDIF – the *Presentation Information* model and the *Semantic Information* model. The Presentation Information model describes how data is presented to the user (e.g. rectangles are used to represent classes, red lines represent inheritance relationships, etc.). Although importers are not required to present data in any particular format, exporters are required to describe how such presentations represent semantic concepts to users. In this way, importers can choose to follow the exporters "recommended" method of presentation, or may choose to present the data in a different, but still semantically correct, way. A more sophisticated tool might even choose to present the data in multiple ways, giving the user various presentation options. In any case, the presentation information is completely separate from the semantic information. The Semantic Information model is actually the CDIF integrated metamodel defined by the various Subject Areas. Together, these Subject Area standards represent the bulk of the CDIF standard.

As stated earlier, CDIF was designed to support the four-layer metamodeling architecture. CDIF has facilities for modeling both syntactic and semantic constructions of a language, and CDIF completely separates presentation details from semantic information. Because metamodel semantics are defined in the various Subject Area specifications, no single semantic modeling technique exists within CDIF. Consequently, CDIF makes no attempt to define a constraint language. However, CDIF does allow constraints to be modeled and transferred between modeling tools, allowing the user to choose a particular tool best suited for verification and/or validation of the metamodels.

Also, because it is primarily a metadata representation and transfer language, CDIF does not have the ability to compose metamodels from smaller, more general specifications.

A Denotational Framework for Comparing Models

A somewhat different approach to metamodeling is taken by Lee and Sangiovanni-Vincentelli [16]. They propose a denotational framework they call a *metamodel*, from within which certain properties of various models of computation can be understood and compared. This framework is a fairly rigorous notation for representing, comparing, and contrasting various notions of concurrency, communication, and time for various models of computation.

This framework uses precise, set-theoretic definitions for *events*, *connections*, *signals*, and *processes*, and identifies the essential properties of various modeling methods, such as discrete-event systems, dataflow networks, rendezvous-based systems, Petri nets, and process networks. The representations of these systems is independent of any implementation details, but provides mechanisms for representing the behavior of such systems. The framework allows process composition, but assumes no specific interaction mechanism.

The system allows for modeling time-based or time-dependent systems, using either continuous or discrete representations of time, through the use of time stamps. Synchronous and asynchronous systems may be represented, containing either sequential or concurrent processes.

Lee and Sangiovanni-Vincentelli state that their system is in its infancy, and not intended to completely define various models of computation, but rather to give the

metamodeler the ability to precisely define the key aspects of behavior contained in well-known modeling methods, and to be able to compare such methods.

Such a denotational framework has the potential to allow a metamodeler to perform various "what if" analyses on competing design techniques. Although the system is designed to represent modeling system semantics, there is no method for specifying the syntax of a modeling language (the framework approach is designed to represent and compare *behavior*, not implementation). There is no direct support for the four-layer metamodeling architecture. The use of set notation to represent modeling language semantics allows concise descriptions of modeling language constraints, and should allow for the parameterized representation of various modeling concepts, but no mechanism for parameterization is addressed. No provision for made for representing constraints as predicate expressions, but again, because of the set-based notation used, such representations would not be difficult to derive.

It is fairly clear that, in its current form, such a denotational framework cannot be effectively used as the metamodeling language for the MGA. Quoting from [16], *"[this framework] is too general for any useful implementation and too incomplete to provide for computation. It is meant simply as an analytical tool. Of course, a great deal of work remains to be done to determine whether it is useful as an analytical tool."* Finally, while this approach does offer a precise semantics for representing concurrent communication processes, and claims have been made that such a system would be useful for comparing various modeling methods, no discussion of how such comparisons would be performed, or of how to interpret the results, are given in [16].

EXPRESS

Since the early 1980's, the International Standards Organization (ISO) has been developing a family of standards to allow the unambiguous computer-based representation and exchange of product information, throughout the product's lifetime, independent of the type of computer system used to create and transfer such a representation. This family of standards is known collectively as the ISO-10303 Standard for Product Data Exchange (STEP). STEP allows for the implementation-independent storage, access, transfer, and archival of product data, and provides a set of criteria for testing a given implementation for conformance to the standard. This standard is becoming widely accepted as a method for integrating design and manufacturing processes.

A STEP representation (i.e. a STEP *model*) forms a single, unified definition of product information that can be used by many design and development tools. To ensure consistent representation and transmission of such information, STEP defines a specification and requirements language called EXPRESS [17]. Because EXPRESS is a formal language, precise and consistent definitions of product information can be created and transferred among various EXPRESS-compliant tools. Part 21 of the STEP standard specifies the Standard Data Access Interface (SDAI) [18], an API and file format for use when exchanging EXPRESS-defined data.

EXPRESS uses attributed entities, relationships, and correctness constraints to represent objects and systems of objects. Constraints are scoped (either local to entities or relationships, or global to an entire information domain), and are specified using a declarative, rather than a procedural, language based on common predicate calculus. Thus, in the context of using EXPRESS as a metamodeling language, static semantics of

a modeling environment can be stated using EXPRESS, and machine-aided proof-checking can be performed on the constraints. (Note: EXPRESS does not require or specify any form of proof-checking.)

The STEP standard is, by definition, a multi-part, extensible ISO standard. Similarly, the core EXPRESS language is supplemented by several extension languages. Two particularly interesting extensions, in the context of MIC, are EXPRESS-X, which allows one EXPRESS schema to be mapped into another, and EXPRESS-G, a graphical representation of EXPRESS. Both are described below.

EXPRESS-X

EXPRESS-X is an EXPRESS-based language that defines one-way mappings between pairs of EXPRESS schemas, where one schema is an abstract representation of the other [19]. EXPRESS-X mappings are defined in a declarative fashion, specifying the conditions under which a new entity should be created. EXPRESS-X combines the earlier languages EXPRESS-M (ISO TC184/SC4/WG5 N243) and EXPRESS-V (ISO TC184/SC4/WG5 N251). Eventually, EXPRESS-X will be extended to support two-way mappings between EXPRESS schemas. EXPRESS-X currently has no support for an EXPRESS metamodel, and cannot support mappings between EXPRESS and other modeling languages. In a series of discussions in [20] regarding new requirements for the EXPRESS-X mapping language, it is suggested that a standard mapping be created from CDIF to EXPRESS, and that developers use CDIF metamodels as a basis for mapping from other notations and languages to EXPRESS. Currently, EXPRESS-X has no support

for metamodeling. One commentator[1] in [20] concludes that if the facilities in CDIF or other JTC1 standards can be shown to be sufficient, an EXPRESS-X metamodeling syntax may not even be necessary. He notes that as long as a standard exists that allows mapping language representations (i.e. metamodels) to a CDIF representation, then those representations can be represented in EXPRESS, since the capability already exists to represent CDIF in EXPRESS. He goes on to say, however, that mapping from EXPRESS to CDIF is not possible, because EXPRESS is semantically richer than CDIF.

EXPRESS-G

EXPRESS-G, the graphical representation of EXPRESS, as defined in Annex B of ISO 10303-11. EXPRESS-G is a formal graphical notation for visually representing EXPRESS specifications. It supports various levels of data abstraction, and can create diagrams that span multiple pages. EXPRESS-G supports a subset of the EXPRESS language, and supports the following types of symbols:

- **Definition symbols**, for denoting simple data types, named data types, constructed data types, and schema declarations.
- **Relationship symbols**, for describing relationships that exist among definitions.
- **Composition symbols**, that enable a diagram to be displayed on more than one page.

EXPRESS-G supports relationship cardinality (i.e. multiplicity), but does not provide any mechanism for including constraints in diagrams. The graphical notation is based on the use of various types of lines, boxes, and shading, and is unique to

[1] This remark was made by Julian Fowler of PDT Solutions, Altrichan, UK.

EXPRESS-G. (Note: OMT [21] and UML [22][23], two very popular graphical specification languages, have graphical notations that are different from EXPRESS-G.)

EXPRESS as a Metamodeling Language

Although EXPRESS does not have specific support for metamodeling, it is semantically rich enough to support definitions of MGA modeling paradigms. Extensions to EXPRESS, such as EXPRESS-M, have been specified using EXPRESS, but EXPRESS-M represents a modified *subset* of EXPRESS (to date, no meta-metamodel of EXPRESS has been specified in EXPRESS). Therefore, EXPRESS does not support the general four-layer metamodeling architecture. EXPRESS does have the ability to express both syntactic and semantic elements of a modeling language, and contains facilities for expressing semantics using invariant mathematical equations, making machine-aided constraint-checking possible. Used as a language to represent MGA metamodels, EXPRESS representations can be validated before using them to generate an MGA-based modeling environment. Also, EXPRESS (via EXPRESS-X and SDIA) is capable of supporting metamodel exchange among EXPRESS-compliant modeling tools.

Model Description Language

The MultiGraph Architecture (MGA) is a toolset for creating DSMEs. The MGA provides a layered software architecture and framework for building domain-specific models [24][25]. The MGA is capable of: (1) constructing, testing, and storing graphical domain-specific models, (2) transforming these models into both analyzable and executable models, and (3) integrating domain-specific applications on heterogeneous computing platforms. The MGA uses Model Description Language (MDL), a text-based

declarative metamodeling language, to define the entities, attributes, and relationships allowed in a particular DSME. Additionally, MDL specifies how these objects are presented to the modeler.

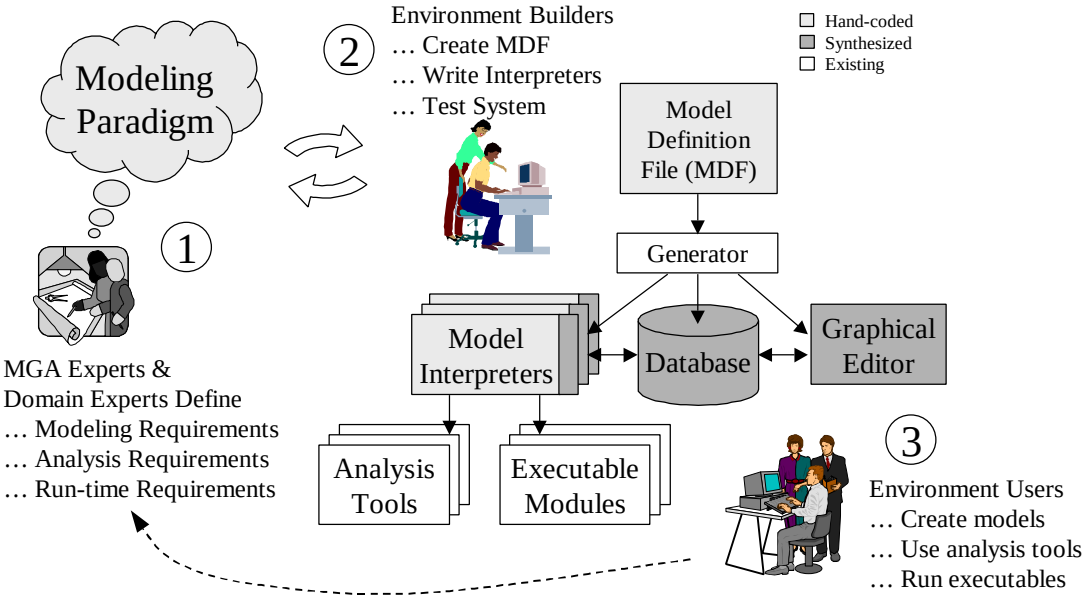


Figure 5: Creating a DSME using the MultiGraph Architecture (MGA)

Figure 5 shows how the MGA is used to create a DSME. The process begins by formulating the domain's *modeling paradigm*. The modeling paradigm embodies all the syntactic, semantic, and presentation information regarding the domain – which concepts will be used to construct models, what types of modeling objects are allowed in the models, what relationships may exist among those objects, how the objects may be organized and viewed by the modeler, and the various rules governing the construction of models. The modeling paradigm defines the *family* of models that can be created using the resultant DSME.

Both domain- and MGA experts participate in the task of formulating the modeling paradigm. Experience has shown that the modeling paradigm changes rapidly during early stages of development, becoming stable only after a significant amount of modeling environment prototyping and testing. Contributing to this phenomenon is the fact that domain experts are often unable to initially specify exactly how the modeling environment should behave. Of course, the modeling paradigm becomes more stable over time. However, because of inevitable changes in the physical system being modeled, neither the modeling paradigm nor the modeling environment can remain static – they must change as the physical system changes. Such modeling environment evolution can invalidate existing models, requiring models to be modified or, in many cases, completely rebuilt. Model migration is very much an open issue.

Once a paradigm is decided upon, the environment builder creates a model description file (MDF) using MDL. The MDF describes the paradigm's model construction semantics – what types of objects may be used to construct models, how those objects will appear on-screen, and how they may be associated (i.e. connected) with each other. The MDF also contains descriptions of any hierarchical and/or multi-aspect model creation and viewing properties that must exist in the modeling environment

The MDF is used to automatically generate the model builder – a graphical model editor – as well as the necessary database schema and database interface code. At this point, the DSME can be used to create models of specific systems within the domain. However, because the MDF specifies only the model construction semantics of the modeling paradigm, no run-time meaning can be inferred from the models. Making sense of the models, i.e. *interpreting* the models, is the job of the model interpreters – semantic

translators that access and process data from the populated model database for use by the analysis tools and executable modules.

Although the MDF and the model interpreter code actually form an informal, de facto specification for the DSME, there is no single specification that can be used to formally validate the consistency of the modeling concepts represented by the MDF and the model interpreters. Paradigm validation is necessary to ensure that the environment sufficiently constrains the modeler so that only legal models can be created. Only a careful examination of the MDF and considerable amounts of testing can uncover such inconsistencies – a time consuming and error prone process. Another drawback of the MGA is the amount of hand-coding required to create a DSME. Except for a small amount of generated interpreter interface code, the MDF and all model interpreters are written completely by hand.

Currently, MDL provides only limited support for the four-layer metamodeling architecture. While it is possible to specify a graphical metamodeling environment using MDL, such an environment would not support the specification of modeling language semantics via provably correct invariant expressions. Instead, a metamodel's semantics would have to be checked using one or more interpreters – clearly not a provable method, since interpreters are written using C++, a high-level procedural programming language. Also, a metamodel translator would need to be developed to ensure interoperability with other metamodeling tools.

Meta Object Facility

The Object Management Group's newly adopted Meta Object Facility (MOF) standard defines a CORBA-based, generic framework for describing and managing meta-

information [26][27]. While defined to represent many types of meta-information, such as CORBA interface definitions, COM objects, and metadata for databases and information services, MOF can also be used to represent and exchange models, metamodels, and project management information for software development tools. These formal models are created using special metamodeling constructs contained in the MOF Model.

The MOF Model

The MOF Model is used to represent entity-relationship models. In other words, the MOF Model is a *metamodel*. The MOF Model contains specific constructs for creating metamodels – *objects*, described using MOF Classes to represent entities (which are object *types*, not specific object instances); *links*, described using MOF Associations, used to show relationships among objects; and *data values*, described by CORBA Interface Description Language (IDL) Types.

MOF Classes allow named, attributed types to be defined in terms of the object's operations and association references. MOF Classes act as containers for component features (i.e. any attributes, operations, and association references). An MOF Class may also contain MOF definitions of CORBA type definitions and exceptions.

MOF Associations are directed, binary associations between exactly two MOF objects. Each Association has two named Association Ends that contain the end's name, its type, its multiplicity (i.e. cardinality), and its aggregation (i.e. whether the end defines a composite object). An MOF Association can be defined to be derived from other model information, and it acts as a container for the two Association Ends.

Other MOF Model elements (called "secondary" elements) consist of Data Types (used for Attribute and Operation parameters), Constants, Exceptions, and Constraints. MOF Constraints are user-defined attachments to model elements. MOF does not require the use of Constraints, and although the MOF Model typically uses OCL [28] as its constraint language of choice, no particular constraint language is defined in MOF. Also, there are also no requirements for any automated constraint checking, should the MOF Model contain constraint specifications.

Just as an MOF Model is a metamodel, an MOF metamodel is actually a meta-metamodel. MOF is a "complete" specification language, capable of defining itself via an MOF metamodel. Such a representation is made using MOF's Meta-Object Definition Language (MODL), a text-based language designed specifically for expressing MOF metamodels. MODL is loosely based on the CORBA IDL syntax. Although MODL was designed to represent MOF metamodels, MOF metamodels can also be represented using the graphical notations of UML [29]. This technique is problematic, however, since, in general, UML contains a richer, more complete set of modeling constructs than MOF. In general, such an approach requires the modeler to carefully specify constraints describing the limitations of MOF. Also, in a few cases, MOF has features that do not map directly from UML (e.g. MOF Attributes and Associations can be derived – UML has no direct representation for such constructs). Typically, this "extra" MOF information is represented using UML Notes. Appendix "D" of [15] explains the metamodel architectural alignment of UML, MOF, and CORBA, and contains various tables comparing the core metaobjects and data types in each standard. The appendix also covers various issues related to mapping between an MOF metamodel and the CDIF

meta-metamodel. It is interesting to note that although the metamodeling constructs of MOF are a superset of the constructs found in the CDIF meta-metamodel, CDIF uses significantly different (and sometimes non-object oriented) terminology.

MOF was designed to support the four-layer metamodeling architecture. MOF supports the representation of both syntactic and semantic language specifications, allowing, but not specifying, a constraint language. Therefore, no mechanism is specified for composing MOF models from pre-specified, generalized modeling constraints. Also, MOF model validation is totally dependent on the particular constraint language chosen. Finally, MOF has no standard file-based format for metamodel interchange between metamodeling tools. One solution proposed in [29] is to use the CDIF transfer syntax to enable tool interoperability.

Formal Methods

Many formal languages exist for specifying a system's behavior. However, few provide mechanisms that support the composition of metamodels from pre-specified, generalized modeling constraints. Two notable exceptions are Specware [30][31], a formal specification language based on category theory, and Larch [32], a module-based formal specification language. Because formal methods represent a new and distinct approach to metamodeling, readers unfamiliar with the terms and concepts of formal methods are referred to Appendix B for a discussion of formal specification, formal verification, and theorem proving.

There are four main goals when deciding on a formal language for use in defining modeling languages (i.e. creating metamodels):

- The formal language must be able to represent the types of constraints that the metamodeler expects to encounter.
- Metamodels must be able to be assembled from general, pre-existing specifications of model composition constraints. Said another way, the formal language must support incremental refinement and composition of specifications.
- The formal language must support a theorem prover.
- The metamodeler must be able to transform the metamodel into a form suitable for use by the MGA.

The basic concepts specified in a metamodel can generally be expressed as operations on sets, and as such, can be represented by any formal language based on predicate calculus. (See [33] for an example of mapping OMT object model notations to Larch.) Of more concern is the ability of a formal language to allow composition of specifications. Only by allowing formal specifications to be composed quickly and hierarchically can non-mathematical modelers be expected to embrace such mathematically intensive methods.

Composition can occur via several mechanisms. The simplest method is to include one specification in another. Both Larch and Specware support building specification in this modular fashion. However, only the simplest of compositions can be performed without the ability to parameterize the included specifications. Larch allows parameterized specifications, much like using functions in a procedural programming language. Specware does not support parameterized specification, but uses the process of *translation*. Translation is best illustrated with a simple example. The following partial specification, written in Specware [30], describes a simple binary relation.

```
spec BINARY-RELATION is
      sorts Domain, Range
      op related? : Domain, Range -> Boolean
end-spec
```

This specification states that binary relations consist of domains and ranges (Specware uses the `sorts` declaration to identify types). The Boolean operation `related?` allows the specifier to assert that domains are related to ranges. Although any metamodeling language must be capable of specifying binary relations among modeling objects, a specification such as this is too general for use in a particular metamodel. However, by importing and translating the sorts and operation contained in this specification, a more domain-specific specification, called `CONNECTION`, can be created. This process is called *refinement*, and is shown below.

```
spec CONNECTION is
      translate BINARY-RELATION by
      {     Domain   -> Source,
            Range    -> Destination,
            related? -> connected? }
end-spec
```

The resultant spec, `CONNECTION`, can now be used to specify a connection that consists of a source connected to a destination. Of course, the specification can be refined further, to apply the `CONNECTION` specification to a particular `Source-Destination` pair.

Although not specifically designed to support metamodeling, formal languages such as Specware and Larch can be used to specify the syntactic and semantic behavior of a modeling language as invariant predicate expressions. The problem is one of scale. Formal languages require low-level definitions of such behavior, and an accompanying

mathematical description of the mechanisms supporting such behavior. Without the ability to compose basic, generalized specifications of behavior (i.e. relationships, hierarchy, object association, etc.) into domain-specific, higher-level specifications, metamodelers cannot be expected to use formal methods. One popular method of including formal methods in software design is to use them to specify only the most critical portions of a design [34]. Also, both Larch and Specware include proof-checkers, allowing the consistency of metamodels to be validated. However, neither language supports the exchange of specifications with other formal methods languages.

Unified Modeling Language

The Unified Modeling Language is an OMG-approved modeling language for specifying, constructing, visualizing, and documenting the artifacts of a software-intensive system [22][23]. It combines concepts from the Booch Method, Rumbaugh's Object Modeling Technique, and Jacobson's Object Oriented Software Engineering method. UML supports many modeling notions, such as use-case diagrams, class diagrams, behavior diagrams (including state charts, state machines, activity diagrams, sequence charts, and collaboration diagrams), and implementation diagrams. UML is a specification language, and as such it does not cover tool specifications, diagram layouts, coloring, user navigation, and other presentation issues.

UML supports the four-layer metamodeling architecture, and UML can be used to model itself [28][3]. When modeling a modeling language, UML has facilities for capturing the syntax and the semantics of the modeled language. The language's syntax is captured in the form of graphical, entity-attribute-relationship and behavioral diagrams, and the language's semantics are represented as invariant predicate logic expressions

using the Object Constraint Language (OCL). Because UML provides no method for incorporating constraints into the graphical models, there is a natural separation between syntactic and semantic specifications. (It is up to the implementation environment to provide support for consistency checking between entity and relationship identifiers in the graphical models and the semantic constraint specifications.)

UML does not identify any method for composing metamodels from generalized, graphical modeling specifications. This stems primarily from the fact that no standardized textual representation of the UML is specified. Therefore, no method of creating parameterized specifications is possible. While this could be considered an implementation detail, it actually represents a serious drawback when trying to use UML as a metamodeling language. Rational Rose [23], a UML modeling tool produced by the Rational company (whose founders are also the designers of UML), uses a somewhat proprietary file format called Rational Petal, and although Rational licenses the Petal technology, it is not in the public domain. To enable tool interoperability, the UML developers have created a UML-compliant tool interface definition using the CDIF standard.

Object Constraint Language

As mentioned above, UML uses OCL to specify modeling language semantics. OCL is a public domain, formal language specification, used to express constraints and other expressions associated with graphical models. OCL is a textual language, designed to be used in conjunction with, but independent of, UML. The full OCL specification can be found in [28]. OCL is a full-featured declarative language, capable of creating expressions that represent complex relationships among object types (OCL can also be

used to create constraints on instances of those types). Although OCL is formal, and has an exact syntax, it was designed to be easily read and understood by human designers.

OCL is not a programming language, and OCL expressions have no effect on the actual system design. The expressions are merely formal comments on the construction and behavior of the system and its components. Designers make statements about required states of models, but OCL cannot cause any state changes in those models. Since OCL is a typed language, for OCL expressions to be correct they must be type conformant (e.g. a designer cannot compare string values with Boolean values). Enumerated types are also supported.

OCL statements represent invariant Boolean expressions that specify the semantics of a modeling language. As an example, consider the MGA audio processing modeling paradigm discussed earlier. It was mentioned that an important consideration when creating actual audio systems is that power amplifier outputs must be connected to something (i.e. power amps should not operated without a load). The following OCL expression states such a requirement.

```
PowerAmp.allInstances->forAll(p | p.OutputConnections->size > 0)
```

This expression states that the number of output connections associated with each instance of a PowerAmp-type object must be greater than zero. Note that this expression represents a condition that must exist in *all* models created using this audio processing modeling paradigm. Also, such a constraint can only be verified in the presence of an actual audio model – an *instance* of the metamodel describing this domain-specific modeling environment.

OCL has facilities for representing pre- and post-conditions, guards, and invariants. It contains many predefined object types (e.g. integer, real, set, collection, etc.), as well as operations on those types. In addition to making formal statements about objects and methods, OCL can be used to describe pre- and post-conditions involving those objects.

Because both UML and OCL are industry standards, developed by a large consortium of industry leaders, they enjoy wide popularity and have been used in many modeling applications. Public domain parsers exist for checking OCL specifications, and several public domain and commercial UML software development environments are available.

Summary of Metamodeling Languages

The following table summarizes and compares the various metamodeling languages discussed in this chapter, according to the criteria set up in Chapter 3.

Table 3: Comparison of metamodeling languages

Language: / Capability:	Aesop, Armani	AML	CDIF	DF	Express	MGA	MOF	Larch, Specware	UML/ OCL
Four-layer support			X			limited	X		X
Abstract syntax modeling	X	X	X	X	X	X	X	X	X
Static semantic modeling	X	X	X	X	X	limited	X	X	X
Metamodel composition								X	
Constraint language		X			X			X	X
Proof checker								X	
Metamodeling tool interoperability		X	X		X	limited	X		

Table 3 clearly indicates that no one metamodeling language contains all the capabilities necessary to add a complete metamodeling layer to the MGA. However, certain languages could be used in combination, capitalizing on each language's particular

strength or capability. The work in this dissertation is based on such a combinatorial approach.

Preliminary Work

To demonstrate the feasibility of, lay the groundwork for, and generate interest in, this research, the following preliminary investigations were performed.

OMT/Specware-Based Metamodeling

The goal of this investigation was to develop a method for specifying a simple domain-specific modeling environment visually using Object Modeling Technique (OMT) [21], translating the OMT specification into Specware first-order predicate logic expressions, composing those expressions into a metamodel, and synthesizing the modeling environment from the metamodel.

Two model composition constraints included in this example are module interconnection and object association (refer to Table 2 above). The example also demonstrates how to incorporate domain-specific constraints into a metamodel. The two constraints chosen were constrained binary relationships and multiplicity.

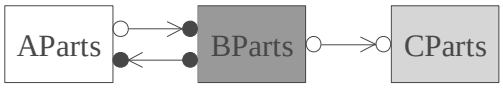


Figure 6: Graphical metamodel

Figure 6 is an OMT object diagram which represents the modeling domain used in this example. This OMT diagram is a graphical metamodel which describes and

constrains object relationships in the target modeling domain. Object types are modeled as named boxes. Lines between boxes indicate which object types can be connected together, the arrowheads[2] indicate the destination object when connecting pairs of objects, and circles indicate connection multiplicity – how many of each object can be connected together. (Hollow circles indicate zero or one object, while darkened circles indicate zero to many.) For example, Figure 6 indicates that two kinds of connections can exist between AParts and BParts objects – one where AParts object play the role of source, and the other where AParts objects play the role of destination. When AParts objects are playing the role of source, each AParts object can connect to any number of BParts objects, and each BParts object can have a connection from at most one AParts object. Consider the following instance diagrams based on the metamodel of Figure 6, where a_n objects are of type AParts, b_n objects are of type BParts, and c_n objects are of type CParts.

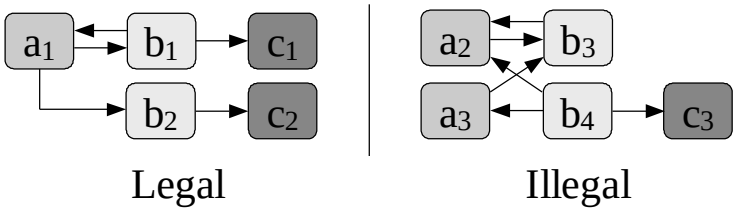


Figure 7: Two domain models based on the metamodel of Figure 6

The model on the left is legal, since it conforms to the connection constraints specified in the metamodel. However, the model on the right is illegal. The metamodel

[2] OMT uses a numbering scheme to indicate the source and destination when connecting objects together. Arrowheads have substituted for clarity in this example only.

requires that any object of type BPart be the destination of at most one AParts-to-BParts connection – not the case with object b_3 which is the destination of connections from both a_2 and a_3.

Formal specification language

As indicated above, a model is said to be *legal* (or *valid*) if it conforms to a given modeling paradigm. A model is *correct* if it faithfully represents reality. Assuming that the modeling paradigm is correct, we can state that all correct models are valid models. However, the converse may not be true – valid models are not necessarily correct models. For example, imagine that an existing power plant is being modeled, but the modeler fails to include a critical plant component, such as an over-current detector. In this case, the model is valid (the modeling paradigm does not *require* over-current detectors, but merely *allows* them), but incorrect – it does not represent reality. However, if the modeling paradigm required every model to include the over-current detector, the model would be invalid.

Why draw such a distinction? Looking again at Figure 7, how does one become convinced that the model on the right is, in fact, an illegal model? Only by *reasoning* about a particular domain model in light of the metamodel can the domain model's validity be determined. And while reasoning in this manner may work for small metamodels, as the size and complexity of the modeling paradigm grows, the metamodeler cannot be expected to validate a metamodel by mental reasoning alone. If,

however, the metamodel is expressed in a formal specification language, the metamodeler can use a computer to aid in the task of ensuring metamodel consistency[3].

As discussed earlier, there are several factors determining the choice of formal language. For this example Specware was chosen for it flexible representational abilities, and its ability to compose and refine general constraints into detailed constraints.

Object association and multiplicity

Formal languages are most helpful when the domain of interest can be represented using set theoretic notation. The following discussion, based on work done by Bourdeau and Cheng [8], shows how Specware specifications can be developed from OMT diagrams. Specifically, the focus is on two important requirements of our example – the number (multiplicity) and type (object association) of objects that can be connected together. To develop these requirements into formal specifications it is necessary to examine the mathematical foundation of object association and multiplicity.

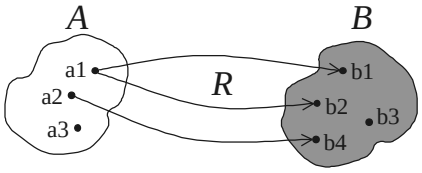


Figure 8: Set theory representation of an injective relationship

[3] Consistent metamodels will lead to modeling environments which are *better* able to prevent a system modeler from building invalid, if not incorrect, models. Inconsistent metamodels will almost certainly lead to incorrect models!

Figure 8 is an example of a relationship *R* between *A*- and *B*-type objects. The diagram shows that every element of *B* is related to at most one element of *A*. Such a relationship is called an *injective binary relationship between A and B*. The relationship can be written as a relational predicate as follows.

$$\forall\ x, y{:}A, b{:}B\ .\ (R(x, b) \wedge R(y, b) \Rightarrow x{=}y) \qquad (1)$$

This equation states that for all *x* and *y* of type *A* and all *b* of type *B*, if *x* is related to *b* and *y* is related to *b* then *x* must equal *y*.

Table 4: Basic relationships used to develop multiplicity constraints

Functional (*R*,*A*,*B*)	Every element of *A* is related to *at most* one element of *B*
Injective (*R*,*A*,*B*)	Every element of *B* is related to *at most* one element of *A*
Surjective (*R*,*A*,*B*)	Every element of *B* is related to *some* element of *A*
Total (*R*,*A*,*B*)	Every element of *A* is related to *some* element of *B*

Table 4 describes the four key relationships needed to formally describe binary object associations with multiplicity. By combining these relationships, any binary object association with multiplicity can be described.

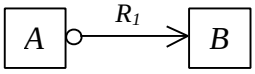


Figure 9: A zero-to-one to one binary relationship

Figure 9 shows an OMT relationship that allows zero or one *A*-type objects to be associated with exactly one *B*-type object. Such a relationship can be described by the conjunctive predicate formula

$$R_1(A, B) = \text{injective}(A, B) \wedge \text{total}(A, B) \wedge \text{functional}(A, B). \quad (2)$$

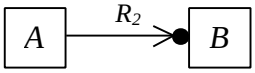


Figure 10: A one to zero-to-many binary relationship

Similarly, Figure 10 shows a relationship that allows exactly one *A*-type object to be associated with zero or more *B*-type objects. This relationship can be written as

$$R_2(A, B) = \text{surjective}(A, B) \wedge \text{injective}(A, B). \quad (3)$$

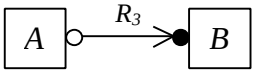


Figure 11: A zero-or-one to zero-to-many binary relationship

By combining OMT diagrams, new diagrams can be obtained. Figure 11 shows the result of combining the diagrams in Figure 9 and Figure 10 to obtain a zero-to-one to zero-to-many relationship. Mathematically, this relationship becomes

$$R_3(A, B) = R_1(A, B) \cap R_2(A, B) = \text{injective}(A, B). \quad (4)$$

Thus, new relationships can be formed by taking the *intersection* of existing relationships. This important concept allows complex specifications to be composed from existing, more general specifications, as discussed in the previous section.

Specification code

The following Specware code fragments demonstrate the key metamodeling concepts contained in this example. A complete code listing is available from the author upon request. The code begins with a simple specification describing a binary connection.

```
spec BINARY-CONNECTION is
      sorts Src, Dst
      op conn : Src, Dst -> Boolean
end-spec
```

`BINARY-CONNECTION` introduces the concept of a connection which has one source (`Src`) and one destination (`Dst`). Also introduced is the Boolean operation `conn` which takes a source and destination as arguments and returns true if they are, in fact, connected together.[4]

Because `BINARY-CONNECTION` is intended to be used exclusively to derive other specifications, no axioms or operational definitions are included with it. Also, the sort `Boolean` need not be explicitly defined – it is built into Specware.

[4] This is somewhat of a misnomer. Specware specifications such as this do not "know" about any particular connection instances, but instead form Boolean constraint equations that must remain valid.

Next, a CONSTRAINED-BINARY-CONNECTIONS specification is created by importing the BINARY-CONNECTION specification. This type of inclusion is similar to the C programming language #include preprocessor directive. CONSTRAINED-BINARY-CONNECTIONS contains the signatures and definitions for the four key multiplicity operations previously listed in Table 4.

```
spec CONSTRAINED-BINARY-CONNECTIONS is
      import BINARY-CONNECTION
      op injective?:(Src, Dst -> Boolean) -> Boolean
      op surject?  :(Src, Dst -> Boolean) -> Boolean
      op funct?    :(Src, Dst -> Boolean) -> Boolean
      op total?    :(Src, Dst -> Boolean) -> Boolean
      definition of injective? is
      axiom (iff (injective? conn)
        (fa (x:Src y:Src b:Dst)
            (implies(and (conn x b)
                         (conn y b))
                     (eq x y))))
      end-definition
   ...
end-spec
```

For brevity, only the injective? definition is shown. The original specification contains definitions for all four operations.

Using the operations contained in CONSTRAINED-BINARY-CONNECTIONS, a series of specifications can be created which define particular binary connections with multiplicity. For example, the ZO-to-ZM-CONN listed below defines a specification that allows zero-to-one source objects to be associated with zero-to-many destination objects. ZO-to-ZM-CONN contains an op called zo-to-zm? which defines this relationship. As expected from the earlier discussion, this relationship is described mathematically as an injective relationship, so the injective? op appears in the axiom contained within the definition of the zo-to-zm? op.

```
spec ZO-to-ZM-CONN is
      import CONSTRAINED-BINARY-CONNECTIONS
      op zo-to-zm? : (Src, Dst -> Boolean) -> Boolean
      definition of zo-to-zm? is
      axiom (iff (zo-to-zm? c)
            (injective? c))
      end-definition
      axiom (zo-to-zm? conn)
end-spec
```

Although they specify relationships that are constrained with respect to multiplicity, specifications such as ZO-to-ZM-CONN are not useful in and of themselves. Instead, they are placed in a model composition constraints library, and are combined with other specifications to form a complete object interconnection specification.

Recall that in this example the modeling paradigm requires connections involving AParts as sources and BParts as destinations to be of type zero-to-one to zero-to-many. This domain-specific requirement is described by the A-to-B-INTERCONNECTION specification listed below.

```
spec A-to-B-INTERCONNECTION is
      translate
            colimit of diagram
                  nodes
                        S:TRIV, D:TRIV,
                        ZO-to-ZM-CONNECTION,
                        APARTS, BPARTS
                  arcs
                        S -> APARTS : { E -> AParts },
                        S -> ZO-to-ZM-CONN : { E -> Src },
                        D -> BPARTS : { E -> BParts },
                        D -> ZO-to-ZM-CONN : { E -> Dst }
            end-diagram
      by {conn -> ab-connection}
end-spec
```

Here, a Specware *colimit* is formed between specifications that describe the endpoints of the interconnection (APARTS and BPARTS) and a specification that

describes the constrained connection itself (ZO-to-ZM-CONNECTION). Two dummy specifications (S and D, both of type TRIV, each of which contain a single sort E) act as "glue points" during the colimit operation. The colimit creates a new specification from the union of specifications cited in the nodes section of the colimit. The arcs section of the colimit allows the specifier to indicate how the nodes are connected together, and which sorts from each node (i.e. specification) are associated with each other. Thus, the colimit can be seen as a union of specifications with selective sharing of sorts.

The first two lines in the arcs section state that the APARTS and ZO-to-ZM-CONN specifications are associated together, and that the sort AParts is associated with sort Source via the "glue" sort E. In other words, the source of this particular type of interconnection is an AParts type of object. Similarly, the last two lines in the arcs section identify the destination of the connection as a BPARTS object, by associating the sort BParts in the BPARTS specification with sort E of the D specification, which is also associated with sort Dst of the ZO-to-ZM-CONN specification. Although both the D and S specifications contain a sort named E, the E's are unique – sort E of specification D is distinct from sort E of specification S.

Finally, notice that the A-to-B-INTERCONNECTION refines the notion of a connection into the more specific "ab-connection." This is done by translating the conn operation, which originated in the BINARY-CONNECTION specification, into an operation called ab-connection.

This example demonstrates that it is possible to use a formal specification language to create general model composition constraint specifications and refine and compose them into a domain-specific specification. Such an exercise is useful in its own

right, to establish the credibility of a modeling paradigm, to allow formal reasoning of a specification, and to document the system's design in a formal way. However, this is not enough. The metamodeler must be able to take this formal specification and translate it for use in synthesizing the actual domain-specific modeling environment. This is discussed below.

Mediator and MDF generation

Only by generating an MDF can a modeling paradigm's formal specification be fully utilized. Generating an MDF from a formal specification requires detailed knowledge about the application programming interface (API) used by the specification language, so that key information may be extracted from the final metamodel specification and used to generate the MDF.

Specware was written using Refine [35], a programming environment for language design which uses BNF-like notational descriptions of the target language's grammar. Because of this, a Refine-based *mediator* had to be written to examine the resulting Specware data structures, extract the information necessary to generate an MDF, and to generate the MDF itself. Because Specware is an emerging technology, little formal documentation was available on the API used to access the underlying data structures. However, with the help of Specware researchers at the Kestrel Institute, a mediator was developed to generate MDF files from simple specifications – simpler specifications than the example just presented. (The modeling paradigm was the same, but the source specifications contained only carefully written axioms from which the MDF information could be easily extracted.) The generated MDF was then used with the MGA to synthesize a modeling environment which conformed to the specified modeling

paradigm. A more detailed mediator, capable of creating an MDF from the specifications presented in this proof-of-concept example was planned, but not completed.

A GME/MCL Metamodeling Environment

An undesirable feature of the OMT/Specware metamodeling approach is that every detail of the target modeling language has to be formalized and expressed as a set of Boolean predicate logic equations. While predicate logic is well suited to expressing the semantics of a modeling language, the syntax and presentation specifications need not be so formally described. This section describes another method that was investigated for metamodeling – to use the GME modeling environment to model a domain-specific modeling language.

A GME modeling paradigm capable of modeling other GME modeling paradigms must have a way to model the target language's semantics, and later, when the target environment is synthesized and used for modeling, those constraints must be enforced. Although the existing MGA tool suite appeared suitable for specifying syntax and presentation requirements, no method existed for specifying and enforcing semantic constraints.

The solution required three modifications to the existing MGA tools. First, a predicate logic constraint language had to be specified and incorporated into the GME. Second, a metamodeling paradigm capable of specifying GME-based modeling languages had to be created. And third, a model interpreter had to be written that could synthesize the target modeling environment from the metamodel.

OCL was investigated for use as the semantic constraint language. It was determined that OCL had the necessary constructs, but lacked any ability to supply any

scope information. Therefore, a modified version of OCL was developed – the MGA Constraint Language (MCL). MCL is strongly based on OCL. Analysis of MGA metamodeling requirements showed that only a subset of OCL would be necessary to express the necessary constraints, but that some additions were needed to efficiently apply OCL to a GME-based metamodeling environment. To that end, functions were added to MCL allowing the metamodeler to specify groups of modeling objects typically found in metamodels. Two such functions are parts("partType") and models("modelType"), both of which represent a collection of modeling objects of a certain type. It was decided that the constraints would be included within the metamodel, not specified separately, allowing the constraints to take on a contextual scope depending on where they appeared within the metamodel. MCL constraint expressions appear inside context specifying "wrappers" and have the following general form:

```
[in category[.model[.aspect]]]
on event constraint name([arguments])
priority=0|1|2|3
"errorText" {
      expression
}
```

The square brackets indicate optional items. The terms `category`, `model`, and `aspect` refer to the GME category, model, and aspect where the constraint is found (i.e. the context where the constraint applies). `event` refers to the type of event that triggers a check of the constraint, e.g. `on_demand` (when specifically requested by the modeler), `on_create` (when a model is created), `on_save` (when a model is saved), etc. `constraint` is a required keyword, `name` is the name of the particular constraint, and `arguments` is a comma separated list of optional arguments, allowing one constraint to

refer to another. The `priority` statement determines when a particular constraint expression is checked relative to other constraints. In this way, a temporal relationship may be established among constraints, where constraints with a higher priority (i.e. a larger priority number) are checked before lower priority constraints. `errorText` is a double-quoted string containing text that is displayed when the constraint is violated. `expression` is the actual Boolean constraint expression.

The final modification to the MGA modeling tool was the creation and addition of a constraint manager (CM). The behavior of the CM is specified in the metamodel by writing constraints as just described. Once the target modeling environment has been synthesized from the metamodel, the CM is configured from the constraints, and the CM monitors the user's model editing actions, alerting him/her whenever a constraint is violated.

The GME/MCL metamodeling paradigm allows the metamodeler to specify objects in the target environment as attributed entities representing atomic parts, models, reference parts, attributes, and categories. Relationships among these objects are modeled as connections or conditionalizations (collections of dissimilar modeling objects). In the case of atomic parts, a visualization object must be attached to the atomic part, indicating how the part will appear in the target modeling environment.

Object hierarchy is modeled via containment. Categories contain Models, Models contain Aspects, and Aspects contain parts, connections, and conditional groups. Note that although Aspects are modeled as first-class modeling objects, in reality they are merely a visualization technique, not actual GME modeling entities. This approach was taken because (1) it was much simpler to design a metamodeling paradigm where

hierarchical containment was uniformly applied to Categories, Models, and Aspects, and (2) novice metamodelers[5] typically think of and use Aspects as "real" objects, so this approach enables them to more rapidly construct metamodels.[6] Also, modeling Aspects in this way does not detract from their use, or restrict their functionality in any way.

[5] Those who have never created a modeling paradigm "by hand," using a purely textual representation.
[6] Expert metamodelers also found this representation intuitive and useful.

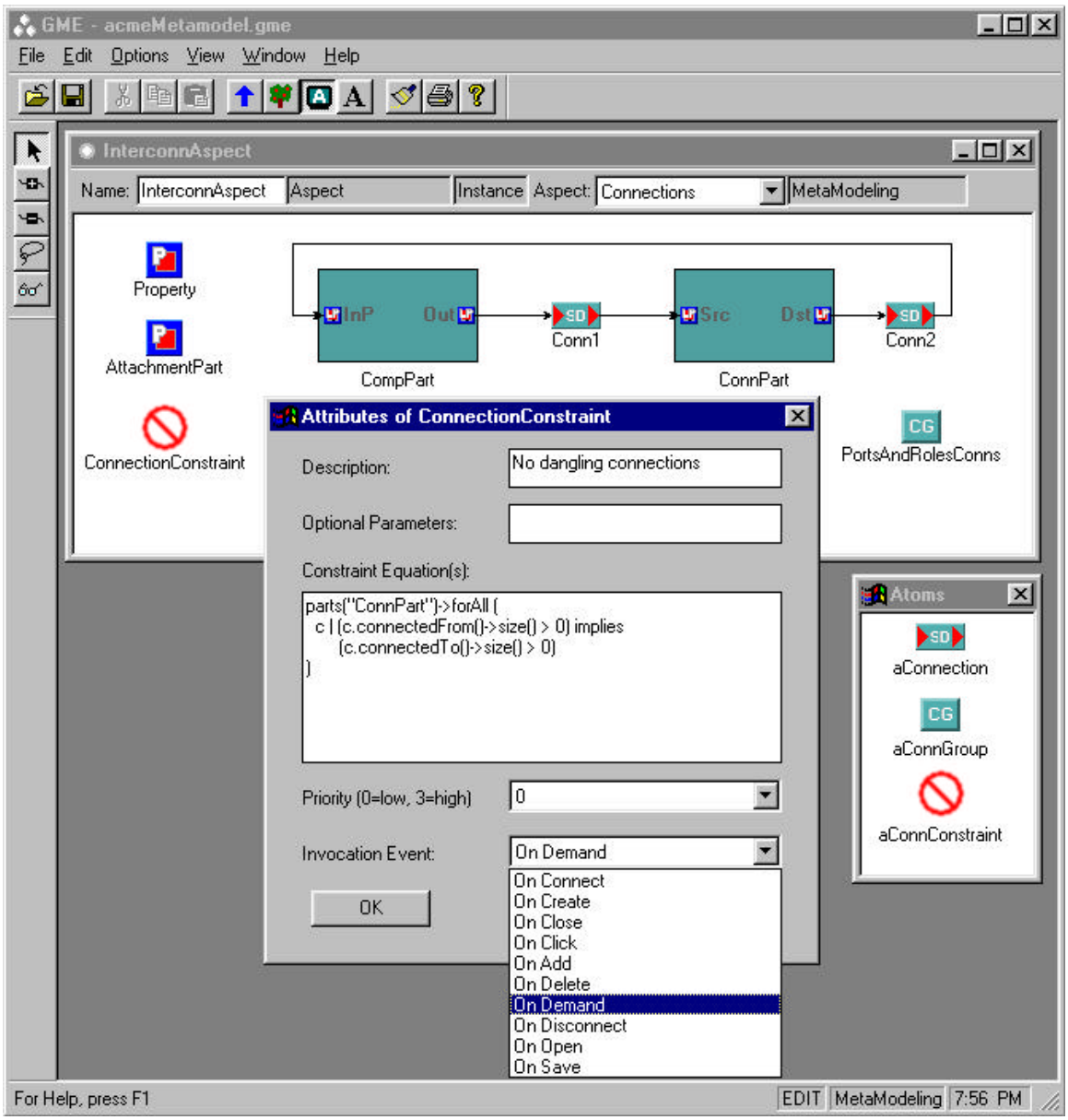


Figure 12: ACME metamodel showing a connection constraint

Figure 12 shows the GME/MCL metamodeling environment being used to develop an ACME metamodel. Here the syntactic and semantic modeling of connections between Components and Connectors is specified. The graphical construction consisting of a CompPart (a Component-type object), a ConnPart (a Connector-type), a Conn1, and a Conn2 (two general connection point objects) specifies the syntax of an allowed type of

connection in the ACME modeling language, while the ConnectionConstraint (whose attribute box is shown opened for editing) is used to specify the connection's semantics. This particular constraint states that if an ACME Connector has a connection to its Src role (i.e. a connection exists *from* another object to the Connector object) then a connection must also exist from the ACME Connector *to* another object. Thus the constraint name "No dangling connections."

Analysis and Lessons Learned

The OMT/Specware metamodeling environment research successfully demonstrated the feasibility of several key metamodeling concepts, such as formal specification of modeling constraints, composition and refinement of specifications, and automatic synthesis of domain-specific modeling environments from metamodels. Analysis of the resulting metamodels showed that although such a predicate logic based metamodel lends itself to computer aided consistency and validation checking, because it consisted entirely of Boolean predicate equations, the metamodel contained far too much low-level detail, and was not easily understood by humans unfamiliar with first-order predicate logic. Also, although metamodel composition was shown to be a viable method for constructing metamodels, the composition techniques used were not generalizable, but relied heavily on Specware-specific composition and refinement techniques. Overall, the OMT/Specware method was deemed unsuitable for use as a general metamodeling method. Nonetheless, the concepts of composing a metamodel by combining and refining general model composition constraints, and generating a domain-specific modeling environment from the metamodel, were successfully demonstrated.

The GME/MCL-based metamodeling environment showed much more promise. Using graphical constructs to specify modeling language syntax was shown to be a viable technique for creating metamodels – a technique that did not unduly burden the metamodeler with low-level formal details. Specifying syntactic and presentation requirements graphically was easier and more intuitive than the Boolean equation refinement method used in the OMT/Specware-based metamodeling environment. By employing MCL to specify semantic constraints, metamodelers were able to create metamodels that properly constrained users of the target modeling environment, preventing illegal models from being created.

Although an improvement over the OCL/Specware approach, the GME/MCL method had several drawbacks. The graphical notation used for syntactic specification was non-standard and, in some cases, non-intuitive. The GME/MCL metamodeling paradigm itself conformed very closely to the MDF syntax and structure, providing essentially the same design choices that are available when creating and MDF by hand (with one important exception – the MDF has no facility for including MCL constraint expressions). This required the metamodeler to be quite familiar with the MDF syntax and semantics, as well as the GME/MCL metamodel construction rules, to ensure success when creating metamodels. In practice, novice metamodelers faced a fairly steep learning curve when using the GME/MCL metamodeling environment, but were generally successful at creating complex metamodels. Expert metamodelers were also successful, but complained that the system seemed more burdensome than simply creating an MDF file by hand. Again, this is because the metamodeling environment provided the metamodeler with few new ways of thinking about modeling language design.

The most severe drawback of the GME/MCL metamodeling environment was its inability to cleanly separate the three language specification components – semantics, syntax, and presentation – from one another. In many cases, presentation requirements were stated in the same design context as semantic and/or syntactic requirements. This had the effect of blurring the design process, forcing the language designer to design in multiple domains simultaneously, making it difficult to think and design abstractly during the early stages of metamodel design. It should be noted that this is also a significant drawback when creating MDF files by hand.

CHAPTER III

UML/GME METAMODELING

Based on lessons learned in creating the OMT/Specware and GME/MCL metamodeling environments, a metamodeling environment based on UML and the GME has been created. The general design methodology utilizes UML to specify the modeling language syntax and MCL to specify semantics. Presentation specifications take the form of a mapping between the UML entities and relationships and GME objects representing elements of the target modeling environment. This approach provides the necessary division between the semantic, syntactic, and presentational elements of the desired language, thus allowing the language designer to focus on one aspect of the language design problem at a time, while simultaneously being able to monitor and track the progress of the overall design. Also, because UML is a well known and widely accepted modeling language, end users can more easily participate in and contribute to the modeling language specification process.

Before discussing the details of specifying language components in the UML/GME metamodeling environment, and the general strategy for mapping the UML-based design notions onto GME modeling objects, it is necessary to understand the various resources available in a general GME-based MIPS modeling environment.

Modeling Environment Resources

Various capabilities exist in every GME-based MIPS modeling environment. To the metamodeler, these appear as modeling environment resources that can be used (i.e.

mapped onto) to express and realize the various features of a particular modeling language. These include the ability to create and edit multi-aspect models of domain-specific systems, to compose models using standardized modeling techniques such as hierarchical decomposition and module interconnection, to specify modeling language constraints which will be enforced when the target language is used for modeling, to store and retrieve models from persistent storage, and to perform semantic translation on the models. This semantic translation represents a second mapping – an automatic mapping performed by one or more model interpreters. This is discussed in more detail in Chapter IV.

Model Creation and Visualization

The Graphical Model Editor

In any visual modeling environment, the key element is the graphical editor used to create the domain-specific models. Generally, this editor serves two purposes: to control the modeler's access to the various editing capabilities of the environment, and to provide visual feedback on the current state of any models being created. In both the UML/GME metamodeling environment, and in the target modeling environment, the GME is used for graphical modeling. Refer to [36] for more information on using the GME as part of the MGA metaprogrammable toolkit.

The GME is a *configurable* editor, taking behavioral cues from various specifications contained in the metamodel. The metamodel must specify the types and characteristics of all modeling parts, part references, and part collections, as well as allowed connections and relationships between parts. Depending on the type of model

being designed, the GME presents the modeler with a parts collection applicable to the current design context (e.g. the type of model, the current aspect, etc.) For example, an automobile design system may allow various types of models to be created, such as brake system models, powertrain models, etc. When creating a brake system model, only components associated with the brake system, such as a brake pedal, brake fluid reservoir, etc., are available for inclusion in the model. Parts such as transmissions, driveshafts, etc., although part of the overall automobile model, are not available when designing brake models.

In addition to contextually controlling the availability of parts, the GME also contextually controls parts availability *within* a model. Here, certain parts may be available and/or visible in one design context but unavailable or hidden in others. These model-specific contexts are called *aspects*.

Multi-Aspect Modeling

The modeling paradigm states how various components of a modeling environment are presented to the modeler. The model design space is partitioned into aspects – separate design spaces within a particular model. Depending on the aspect chosen, certain modeling parts, part references, and/or relationships (e.g. conditionalizations and/or connections) may or may not be allowed.

More than one aspect can exist within a particular model. For example, consider again the automobile brake system example. Braking systems consist of both mechanical and electrical components and subsystems. Therefore, a brake system modeling paradigm would specify two aspects for a brake model – a mechanical aspect and an electrical aspect. When the mechanical aspect is activated, only the mechanical parts of the system

are visible, and only mechanical models can be constructed. Similarly, when the electrical aspect is selected, only electrical modeling components are visible and available. However, the underlying brake model contains *both* mechanical and electrical components; which ones are visible is determined by the current aspect. Note that in some cases it is necessary for parts to be visible in multiple aspects (e.g. the brake light switch is an integral part of both the electrical and mechanical subsystems, and should therefore appear in both aspects). To enable this behavior, parts are designated as *inherited* across aspects. Each part has a primary aspect where it is first created, but can also be used in other aspects if properly identified (in the metamodel) as inherited.

Model Composition

To manage the complexity associated with models, various model composition capabilities are available to the modeler. Object containment provides information hiding and design abstraction by allowing objects to contain other objects, enabling the modeler to selectively view or hide the model's constituent parts. The MGA provides part-whole hierarchy support in two ways – through the use of Models and through Conditionalization.

Model Hierarchy

A Model acts as a container for various types of modeling parts – atomic parts, other models, or *references* to other parts and/or models. Underlying data structures associated with each Model object contain lists of the various parts contained within the Model. These data structures are automatically updated as Model objects are created, edited, and/or deleted. Visually, when one model contains another, the GME represents

the contained model as a solid rectangular box, the contents of which can only be seen by "opening" that model. An exception to this behavior occurs when the contained Model itself contains *link parts*. Links are specially marked atomic parts that can be connected to external parts (i.e. parts of other Models). When one Model contains another Model that contains link parts, the link parts appear on the edges of the contained Model's rectangle, forming attachment points for external connections.

Module Interconnection

Link parts are the mechanism for providing support for module interconnection, one of the general modeling composition constraints listed in Table 2. Through the use of object hierarchy and link parts, modeling paradigms can be developed which implement module interconnection schemes. Note that only atomic parts can be designated as link parts, and that link parts only appear as connection points *one level up* in the containment hierarchy. For example, consider three Models, A, B, and C. If A contains B, and B contains C, and C contains link parts x and y, x and y will be visible on the edges of C when C is viewed from within B, but not when B is viewed from within A.

Conditionalization

The second method for providing part-whole hierarchy is through *conditionalization*. Conditionalization refers to the collecting of atomic parts, models, references, and connections into named groups. A special *conditional controller* part, which itself can be an atomic- or reference part, is designated as the "owner" or "controller" of the parts collection. To add or remove parts from the conditionalization group, the GME must first be put into "conditional mode" (one of the editing modes

available to the modeler). Next the controller must be selected and activated. Once activated, the modeler can then mark/unmark various parts and connection types for inclusion in the conditionalization group.

As an example of conditionalization, consider a power distribution modeling environment consisting of transformers, transmission lines, and switches. Atomic parts are used to represent transformers and switches, while connections between transformers and switches represent transmission lines. Suppose it is necessary to designate certain groups of transformers, switches, and transmission lines as "mission critical" groups, while other groups must be designated as "non-critical." One could design a modeling paradigm containing two types of transformers, switches, and connections – one type to be used when constructing mission critical power diagrams and the other type used when constructing non-critical diagrams. This scheme breaks down, however, when a single component must be a member of both groups (e.g. a transformer feeds both a mission critical circuit and a non-critical circuit – the same transformer must have membership in two groups). Without conditionalization, modeling this type of situation would be complicated and non-intuitive. With conditionalization, however, the solution is straightforward. The modeler creates two conditionalization groups, each with its own controller part, and marks parts as belonging to one or both groups. This assumes, of course, that the metamodel specifies such groups to exist and contain similar types of parts.

Constraint Management

As mentioned earlier, constraints are used in a metamodel to specify the semantics of a particular modeling language. These Boolean predicate expressions

represent invariant conditions which must hold for models to be legal in the given paradigm. In practice, however, the modeler is usually able to create both legal and illegal models. Therefore, some mechanism must exist to ensure that the semantic constraints contained in the metamodel are enforced during model creation time. This is the job of the constraint manager (CM).

Constraints are supplied to the CM from the metamodel. The metamodeler must ensure a proper correlation between the object and type names used in the constraint equations and the object and type names used in the GME. (In the current UML/GME metamodeling system, constraints are simply text strings associated with the metamodel – no type checking is performed to ensure that object names used in a constraint properly correlate to named objects in the paradigm). During metamodel interpretation, these constraints are extracted from the metamodel and stored in a file. The file naming convention is such that the constraint manager expects to find a file with the same name as the modeling paradigm, albeit with an .mcl extension. The metamodel interpreter ensures this occurs. The constraints contained in this file are used to configure the constraint manager when the target modeling environment is activated.

Persistent Storage

In addition to saving and retrieving constraints from the constraint file, a persistent storage scheme is required to store and retrieve models. The GME supports the standard directory/filename scheme for storing and retrieving models from persistent (i.e. disk) storage. No metamodeling constructs are associated with this GME feature – the ability to save and retrieve models from the model database is hard-coded into the GME. However, as in the case of constraints, the default file names are taken from the

metamodeling paradigm name. As explained below, every metamodel must include a single paradigm model.

Semantic Translation

Finally, and perhaps most importantly, the GME-based MIPS modeling environment provides the user with the ability to perform semantic translations (i.e. *interpretations*) on the models. This is accomplished by providing the user with a set of C++ classes that allow access to the underlying MGA data structures. Through these classes, metamodelers write various model interpreters to traverse the data structures, extracting and processing data contained in the models (e.g. analyzing the data and/or translating the data into streams for use by external post-processing programs). Model interpretation may be performed at any time during model construction. The supplied classes provide a single entry point for model interpretation. Of course, interpreter writers must have a detailed knowledge of the types of entities, attributes, and relationships allowed by the modeling paradigm, as well as an understanding of the supplied data access classes.

Currently no capability exists for synthesizing a semantic translator from information contained in a metamodel. However, early research [5] indicates that such synthesis is possible and desirable.

Syntactic and Semantic Mapping

The heart of the UML/GME metamodeling system is the ability to specify and map representations of the target language's syntax and semantics onto modeling components used in the GME. This section describes how various syntactic and semantic

specifications are stated using UML/OCL, and how such specifications are mapped into GME constructs.

UML Class Diagrams

Metamodels use UML class diagrams to specify the objects, attributes, and relationships to be included in the target DSME. The UML/GME metamodeling environment includes a special type of Model, a *UML Model*, for specifying the target language's syntax and semantics.

Syntactic Specification

As discussed in the Background section, when creating the specification for a new modeling language, the designer first specifies the abstract syntax of the language without regard for how such syntax will be presented to the user in the final design environment. In this early language design phase, the designer is only concerned with the target language's basic modeling objects, object attributes, and object associations. These specifications are made using UML class diagrams.

To develop the necessary metamodeling concepts required for specifying MGA modeling paradigms, consider an audio processing system consisting of microphones, preamplifiers, power amplifiers, and speakers. These components can be connected to one another in various configurations, according to certain rules discussed below.

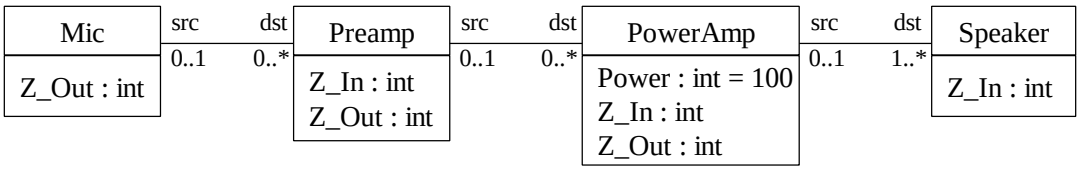


Figure 13: A simple UML audio processing metamodel

Figure 13 shows a simple UML metamodel representing this audio signal processing modeling paradigm. The metamodel specifies the types of modeling objects allowed (e.g. `Mic`, `Preamp`, etc.), object attributes (e.g. `Z_In`, `Z_Out`, etc.), and all associations allowed among the objects. For example, the diagram indicates that every `Mic` object, playing the role of `src`, may be associated with zero or more `Preamp` objects, playing the role of `dst`. Similarly, every `Preamp`, playing the role of `dst`, may be associated with zero or one `Mic`s playing the role of `src`. Note that the `Power` attribute of each `PowerAmp` will be initialized to 100 when `PowerAmp` objects are instantiated (this value may later be changed by a modeler using the target language).

Figure 13 represents the syntactic specification of the audio processing language. However, because UML requires multiplicity constraints on associations, certain semantics specifications will also be present in a UML class diagram. For example, the association between `PowerAmp` objects and `Speaker` objects requires every `PowerAmp` to be associated with *at least one* `Speaker` – a semantic requirement of the language. Notice that input and/or output impedance attributes are also associated with each modeling object.

A refinement of this modeling paradigm can be achieved by incorporating module interconnection modeling principles. Microphones, preamps, power amplifiers, and

speakers can all be modeled as one- or two-port I/O devices, where the ports are used to connect the components together. Specifically, two kinds of ports exist – input and output ports – and certain relationships exist among ports (e.g. signals leave one object via an output port and enter another object via an input port). By restricting the relationships between input and output ports themselves, the relationships among microphones, preamps, power amplifiers, and speakers, which aggregate these ports, are implicitly restricted.

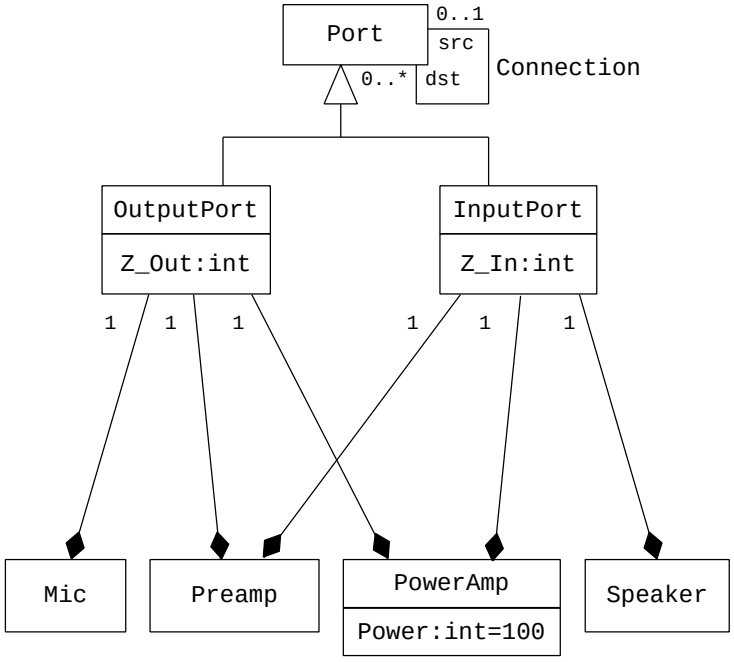


Figure 14: A refined UML audio processing metamodel

Figure 14 shows a refined audio processing metamodel using object hierarchy to derive specialized objects from general ones. The `Mic`, `Preamp`, `PowerAmp`, and `Speaker` objects are treated as *modules*, and a specialized form of association, called a *connection*, is used to connect one module to another. The actual connection is made

between *ports* contained in the modules. If directional connections are to be modeled (as in this example) the ports can be divided into two types – *input* ports and *output* ports. Modules may contain both types of ports, depending on the type of module. For example, a `Mic` contains a single `OutputPort`, while a `PowerAmp` contains both an `InputPort` and an `OutputPort`.

In Figure 14, the `Port` acts as a general module interconnection object. A `Connection` association, with `src` and `dst` roles, is used to associate (i.e. *connect*) one `Port` with another. Notice that `Port`s are not used as first-class modeling objects in this paradigm, but are specialized into `OutputPort` and `InputPort` objects. `Z_Out` and `Z_In` attributes are associated with `OutputPort` and `InputPort` objects, respectively. The final modeling objects are specified as aggregations of one `OutputPort` and/or one `InputPort`. This approach represents an improvement over the metamodel of Figure 13 by more clearly defining object containment, derivation and interconnection, as well as directly associating the impedance attributes with the `OutputPort` and `InputPort` objects.

Static Semantic Specification

While the use of hierarchy allows a modular design approach and makes composing metamodels easier, such an approach generally requires more constraint equations to fully constrain the design. For example, the metamodel of Figure 14 allows full connectivity between *any* two `Port`-type objects (e.g. `OutputPort` or `InputPort` objects), regardless of which type of container object they appear in. This metamodel even allows an `OutputPort` to connect to itself – a condition that is not

permitted in real-world audio processing system, and so should be illegal when modeling such systems. Also, the simplified metamodel of Figure 13 required that every PowerAmp object be connected to something. The refined metamodel of Figure 14 contains no such restriction. Therefore, several constraints must be placed on this refined metamodel.

First, the relationship between OutputPorts and InputPorts must be limited. OutputPorts may connect to InputPorts and InputPorts may connect to OutputPorts. No other connections involving OutputPorts and InputPorts are allowed. The following OCL equation properly constrains this relationship:

```
Connection->forAll(c |c.src.oclIsTypeOf(OutputPort) and
                      c.dst.oclIsTypeOf(InputPort))          (5)
```

This expression states that the src role of every Connection association must be an OutputPort object and the dst role must be an InputPort object.

The interconnections between modules must also be constrained. For example, Mics can only connect to Preamps, Preamps can only connect to PowerAmps, and PowerAmps can only connect to Speakers. The following constraint equations specify these allowed connections:

```
Mic->forAll(m | m.outputPort.dst->forAll(i | i.preamp))          (6)
Preamp->forAll(p | p.outputPort.dst->forAll(i | i.powerAmp))     (7)
PowerAmp->forAll(a | a.outputPort.dst->forAll(i | i.speaker))    (8)
```

Equation (6) allows Mics to connect only to Preamps. Note the use of outputPort (first letter lower case) to refer to the unnamed role at the "Preamp end"

of the aggregation association between the `InputPort` and `Preamp` objects. Because the role is unnamed, OCL allows the name of the associated object (beginning with a lowercase letter) to be used as the association role name. The other two constraint equations function similarly to constrain connections between `Preamp`s and `PowerAmp`s, and between `PowerAmp`s and `Speaker`s.

Table 5: Possible connections without constraints

Dst / Src	Mic	Preamp		PowerAmp		Speaker
	Out	In	Out	In	Out	In
Mic Out	X	X	X	X	X	X
Preamp In	X	X	X	X	X	X
Preamp Out	X	X	X	X	X	X
PowerAmp In	X	X	X	X	X	X
PowerAmp Out	X	X	X	X	X	X
Speaker In	X	X	X	X	X	X

Table 6: Possible connections with constraints

Dst / Src	Mic	Preamp		PowerAmp		Speaker
	Out	In	Out	In	Out	In
Mic Out		X				
Preamp In						
Preamp Out				X		
PowerAmp In						
PowerAmp Out						X
Speaker In						

Using OCL in this way is a powerful method for applying semantic constraints to the modeling language specification. Table 5 shows that if no constraint equations were

used in the refined metamodel of Figure 14, 36 possible connections between the `OutputPort` and `InputPort` objects contained inside the various modules would be possible. By introducing just four constraint equations, the allowable connections are reduced to three, as shown in Table 6.

To complete this metamodel, one more constraint equation is needed. A requirement exists that every audio processing model contain at least one `PowerAmp`. This semantic constraint can only be represented using an OCL constraint equation – the metamodel of Figure 14 *allows* `PowerAmp` objects, but UML has no mechanism to indicate that such objects *must* exist. Equation (9) below makes this requirement explicit.

```
PowerAmp.allInstances->size >= 1                                    (9)
```

GME Object Representation

After the syntax and semantics of a modeling language have been designed, it is necessary to specify the presentation requirements. This is done as a mapping between the UML entities and MetaGME modeling objects representing the various GME modeling objects that will be available for use in the target DSME. This section describes these GME modeling objects, and explores various methodologies for realizing DSME designs using the UML/GME metamodeling environment.

GME Modeling Objects

Regardless of the domain-specific nature of a particular GME modeling environment, the modeling objects, relationships, and functionality present in a given DSME are based on a common set of GME modeling object types and GME environment

features. These include atomic parts, multi-aspect models, part- and model-references, inherited and non-inherited parts, connections, connection groups, conditionalization groups, and categories. These components have specialized functions, properties, and appearances that are configured according to the modeling paradigm, via the metamodel.

In the UML/GME metamodeling environment, GME components must be represented (i.e. modeled) *using the GME itself*. Thus, the metamodeling paradigm must identify the salient characteristics of general GME modeling paradigms and represent those characteristics using the components and methods available in the GME, as just mentioned.

Table 7: Models and aspects of UML/GME metamodeling paradigm

Model Type / Aspect	UML	Attribute	AtomicPart	Model	Paradigm
Entity-Relationship	X				
Constraints	X				
UML->GME Map			X	X	
Attributes		X	X	X	
Parts				X	
References				X	
Connections				X	
Conditionalization				X	
Aspects				X	
Categories					X

Table 7 lists the various types of GME models and aspects defined in the UML/GME metamodel. The Entity-Relationship aspect of the UML model is used to define UML class objects and relationships that represent the modeling language syntax and multiplicity semantics. Other modeling language semantic specifications are contained in the Constraints aspect of the UML model.

Attribute models are used to model the various types of attributes available in the GME. These include single- and multi-line textual fields, Boolean toggle values, and menus. Attribute models may be arranged hierarchically, allowing Attribute models to contain other Attribute models. Arbitrary levels of Attribute hierarchy are allowed in a metamodel. Attribute models consist of only one aspect – the Attributes aspect.

AtomicPart models are used to model GME atomic parts. AtomicPart models have two aspects. The UML->GME Map aspect is used to map a UML object onto a GME AtomicPart object. Every AtomicPart model must include a reference to a single UML class object. The Attributes aspect of an AtomicPart model is used to define which attributes (if any) the modeled atomic part has. Atoms can have an arbitrary number of attributes associated with them. The Attributes aspect contains one metamodeling attribute for specifying a bitmap image to represent the atomic part in the target DSME.

The Model model is the most complex GME metamodeling object, having seven aspects. Before describing these aspects, however, a few comments about models are in order. GME models contain parts (atomic, model, and reference parts), attributes, connection groups, and conditionalization groups. However, the model is partitioned visually according to various aspects associated with the model. The parts contained within a model can be thought of as members of one (and only one) of these aspects. The same is true for attributes, connection groups, and conditionalization groups. In the metamodeling paradigm, parts (models and/or atomic parts) are designated as belonging to a model by placing a copy of the part into the model's Parts aspect. These parts are inherited by another aspect of the model – the Aspects aspect – and it is in this aspect that the metamodeler indicates the desired partitioning. (This is explained in more detail

below, and is demonstrated in the Metamodeling Process section.) In a similar manner, references, connection groups, and conditionalization groups belonging to a particular model are denoted using the model's References, Connections, and Conditionalization aspects, respectively, but are partitioned into the model's aspects in the Aspects aspect.

Returning to the seven aspects of a Model model, as was the case with AtomicPart models, a UML->GME Map aspect is used to associate a UML class object with a GME Model object. The model's Attributes aspect is used to assign various attributes to the model. The Parts aspect contains references to GME AtomicPart and Model models, indicating which parts are contained in the model. Note that to fully specify a part within a model, both a part name and a part type must be known. The metamodeling paradigm uses the name of the part reference as the part name and the name of the UML class object corresponding to the referenced part as the type.

The model's References, Connections, and Conditionalization aspects contain references to UML class objects. This provides a means for mapping UML associations onto one of the object relationship mechanisms supported by the GME (e.g. connections, references, or conditionals). To assign a UML association to a particular kind of GME relationship, a reference to the association's class object is placed in the appropriate aspect (e.g. the References, Connections, or Conditionalization aspect) of the model. During the metamodel interpretation process, group membership is determined by investigating the UML model to determine which types of objects are associated or aggregated together to form the group. Once the object types have been determined, the GME model's Parts aspect is checked for the existence of these types of parts in this particular model. If parts of the proper type exist, they are used to form the actual

members of the relationship group. This is demonstrated in the Metamodeling Process section.

The Aspects aspect of a Model model is used to partition the model's parts, references, connection groups, and conditionalization groups into various visualization aspects of the model. Additionally, the metamodeler may indicate that some or all of the parts and/or connection groups are *inherited* across aspects of the model. Inheritance allows parts and connection groups to appear in more than one aspect of a model.

The final GME model type is the Categories model, which contains a single Paradigm aspect. GME categories are collections of models. These collections are modeled by placing references to GME Model models in the Paradigm aspect of a Categories model, and adding a special Category part, which acts as conditional controller, to create groups of model references. Each group will result in a named category being created in the target modeling environment.

Metamodeling Process

This section brings together all the concepts discussed in this chapter and presents a methodology for designing and creating metamodels using the UML/GME metamodeling environment. The audio processing system previously discussed is further expanded in this section and used to demonstrate key concepts of the metamodeling process.

The expanded audio system contains several new modeling concepts, so new objects and relationships must be added to enable the creation of valid audio processing models. The first object to be added is a Person, which represents the analog input to a microphone. A System object is also added. System objects act as containers for Mic,

Preamp, PowerAmp, Speaker, and Person objects (i.e. a System *aggregates* these objects). Thus a System becomes a collection of Mics, Preamps, PowerAmps, Speakers, and Persons.

Another object, a Performer, is added that represents the relationship between a Person and a Mic. The real-world concept being expressed is that *persons using microphones are referred to as performers*. Furthermore, since each performer has unique audio qualities, preamps are adjusted to tune audio systems for particular performers. Therefore, a RefToPerformer object is added to represent such an association between performers and preamps.

One final association must be added that represent the relationship between microphones and loudspeakers. A microphone represents the source of an electrical signal reaching the loudspeaker. A UML class object named SoundSource is used to represent this association.

Figure 15 below shows the UML class diagram design for the expanded audio processing system. The figure shows the EntityRelationship aspect of the UML-type model, and includes objects and associations to represent the new modeling concepts just described.

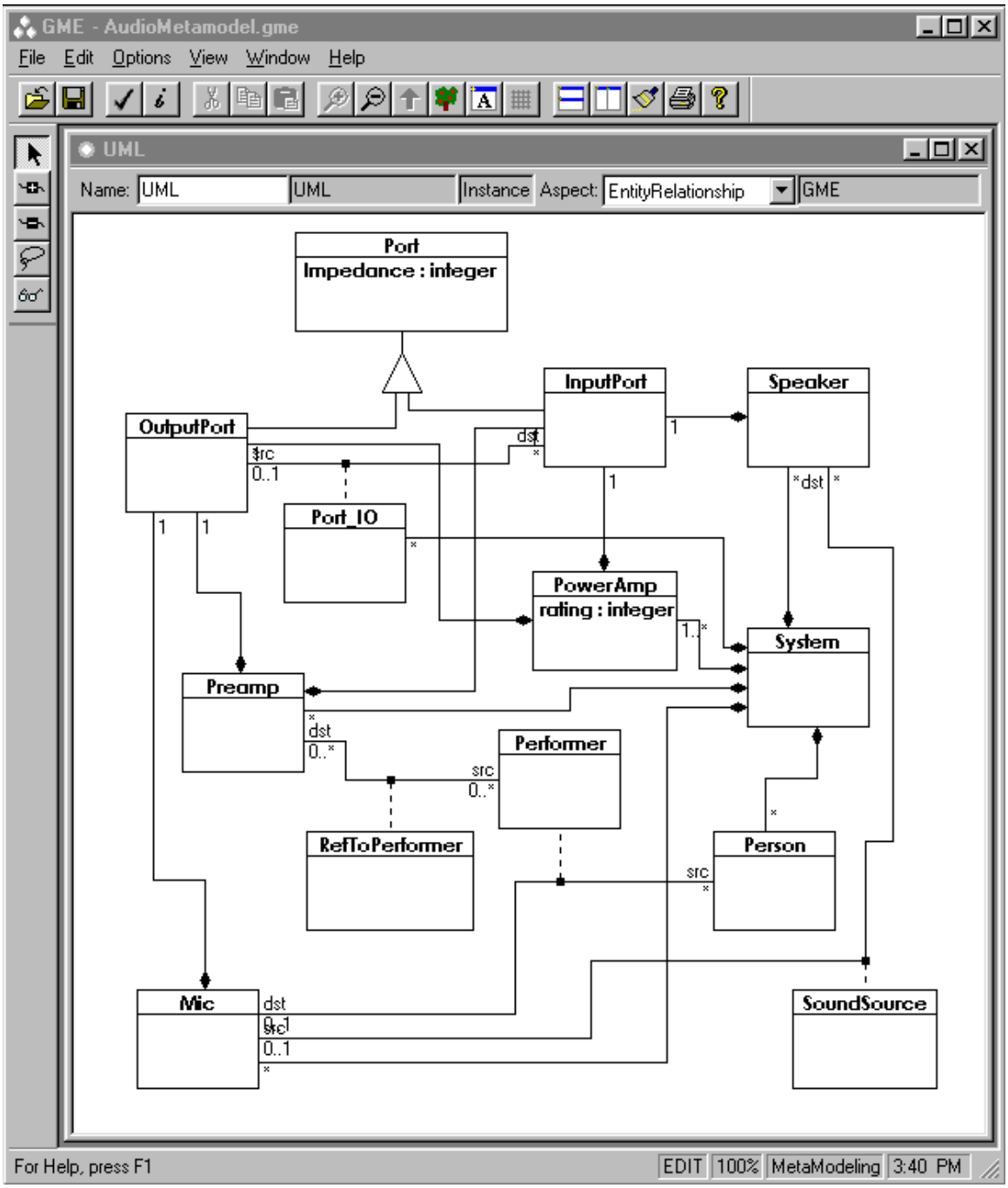


Figure 15: UML class diagram of the expanded audio processing system

The System object, along with the Mic, Preamp, PowerAmp, and Speaker objects, will be mapped onto GME Model models (note that each of these UML class objects aggregates other objects and thus must be represented as a GME model, not an atomic

part). Notice that the System object aggregates the new Person object. As mentioned, Persons represent sound sources to the audio processing system, and are modeled as part of the system. The Person object will be represented as a GME AtomicPart object, since a Person does not contain other objects.

Notice that the previous association between two Port objects (the "Connection" association of Figure 14) has been replaced by the Port_IO association in Figure 15. Port_IO is an association class that represents the association between OutputPort objects and InputPort objects. Since OutputPorts and InputPorts are specialized versions of Port objects, the Port_IO association is a more specialized representation of the association. As mentioned earlier, this is a somewhat less flexible design than that represented in Figure 14, but will result in the need for less constraint equations.

Note that association classes are attached to associations via dashed lines, as shown in the figure. By attaching a class object to an association in this manner, the association itself can be represented by (i.e. mapped onto) a GME connection relationship in a GME Model[7]. Figure 16 shows how the Port_IO association is mapped onto a GME connection relationship.

[7] UML allows named associations with or without an attached association class. However, the GME/UML metamodeling paradigm requires the use of association classes when mapping to a GME connection group relationship.

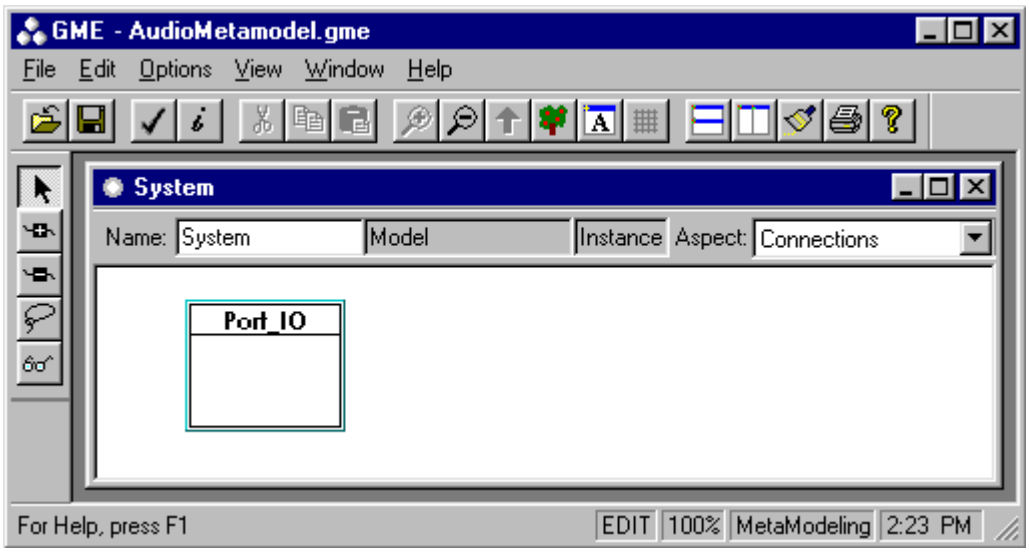


Figure 16: Mapping the Port_IO association into a GME connection relationship

As indicated by Figure 16, all that is necessary to map a UML association to a GME connection relationship is to place a reference copy of the particular UML association class into the Connections aspect of a GME Model model where the connection group is to exist. In Figure 16, the Port_IO association from the Entity-Relationship aspect of the UML model is being mapped as a connection group in the System model. The name of the association (e.g. Port_IO) is used as the name of a GME connection group. Of course, the connection mapping only makes sense if the System model contains atomic parts or models that represent the UML objects acting as the source and destination of the Port_IO association. (If the Port_IO association is mapped to a model that does not contain GME objects representing the UML source and destination types, the connection mapping is considered invalid).

A particular GME Model model may contain several different parts of the same type. Because of this, a GME connection group that represents a single association between two UML class objects may represent a *set* of connections within a model –

hence the name connection *group*. In such cases, the meta-interpreter will resolve all possible individual connections based on the associated UML types, as explained below.

The simplest case of connection resolution occurs when the associated source and destination UML class objects both map to GME AtomicPart models (i.e. connections in the target modeling environment will be between two atomic parts). To resolve all possible connections, the source and destination UML class objects are located (OutputPort and InputPort in this example). The names of these UML class objects represent the *types* of GME objects involved in the connections, and will be used to determine which GME atomic parts can participate in a given connection. Once the source and destination types have been determined, the GME Model model containing the connection group is located, and each Aspect specification within the model is analyzed for the presence of at least one pair of source/destination parts of the proper type. Using the names of the AtomicPart models the UML source and destination class objects map to, a set of GME connections specifications is created. Note that the number of connection specifications depends on the number of atomic parts of the proper type contained in the Model model.

A more complicated case exists when the associated UML objects are aggregated into other UML objects. (Note that these "other" UML objects will map to GME Model models and not AtomicPart models). If the GME model containing the connection group also contains references (discussed below) to parts contained in these "other" GME Model models, connections must be resolved involving those referenced parts – for all possible combinations of source and destination parts of the proper type. Thus, a fairly simple UML connection specification involving aggregated parts can result in a GME

connection group that contains many connections involving both atomic and reference parts (within and without the model containing the connection group). Using the audio processing system of Figure 15, and assuming a single aspect in the System model, the Port_IO association mapping shown in Figure 16 results in a GME connection group containing nine resolved connections, as shown below.

```
Port_IO { 1 solid line butt } :
      { aMic Out -> aPreamp In }
      { aMic Out -> aPowerAmp In }
      { aMic Out -> aSpeaker In }
      { aPreamp Out -> aPreamp In }
      { aPreamp Out -> aPowerAmp In }
      { aPreamp Out -> aSpeaker In }
      { aPowerAmp Out -> aPreamp In }
      { aPowerAmp Out -> aPowerAmp In }
      { aPowerAmp Out -> aSpeaker In };
```

Notice that many more connections are generated than allowed by Table 6. This is because the audio processing system modeling paradigm was designed to allow module interconnection modeling techniques in the target modeling environment, forcing object associations to be specified at a higher, more abstract level in the metamodel. The combination of abstract object association and object aggregation results in a large number of GME connections, many of which may be illegal. This demonstrates the need to compliment such generalized modeling concepts with constraint equations such as equations (6), (7), and (8) and a constraint manager capable of rejecting models that violate these constraints. If the more abstract Port-to-Port association were used, the number of resolved connections would grow much larger, requiring many more constraint equations to restrict the legal connections to those shown in Table 6. However, if the more specialized associations of Figure 13 are used, no constraint equations would be required, but the modeler loses the ability to design using module interconnection

techniques. Thus Port_IO represent a tradeoff, decreasing the number of constraint equations while maintaining modeling flexibility in the target environment.

Also notice that the Z_Out and Z_In attributes of OutputPort and InputPort, respectively, have been eliminated in Figure 15 in favor of a single Impedance attribute contained within the Port object. This Impedance attribute is inherited by the OutputPort and InputPort objects. This approach cleans up the design while maintaining the ability to specify impedance values for each input and output port. Because the OutputPort and InputPort objects will be mapped to GME AtomicPart models, the modeler (and the model interpreter) will be able to distinguish input impedance from output impedance by context.

In addition to Port_IO, three other named associations have been added in Figure 15. The first, Performer, associates a Person object with a Mic object (the modeling paradigm represented by this metamodel requires that each Mic object "know" which Person is using it). Rather than aggregate a Person object into a Mic object, the decision was made to map the Performer association into a GME part reference relationship.

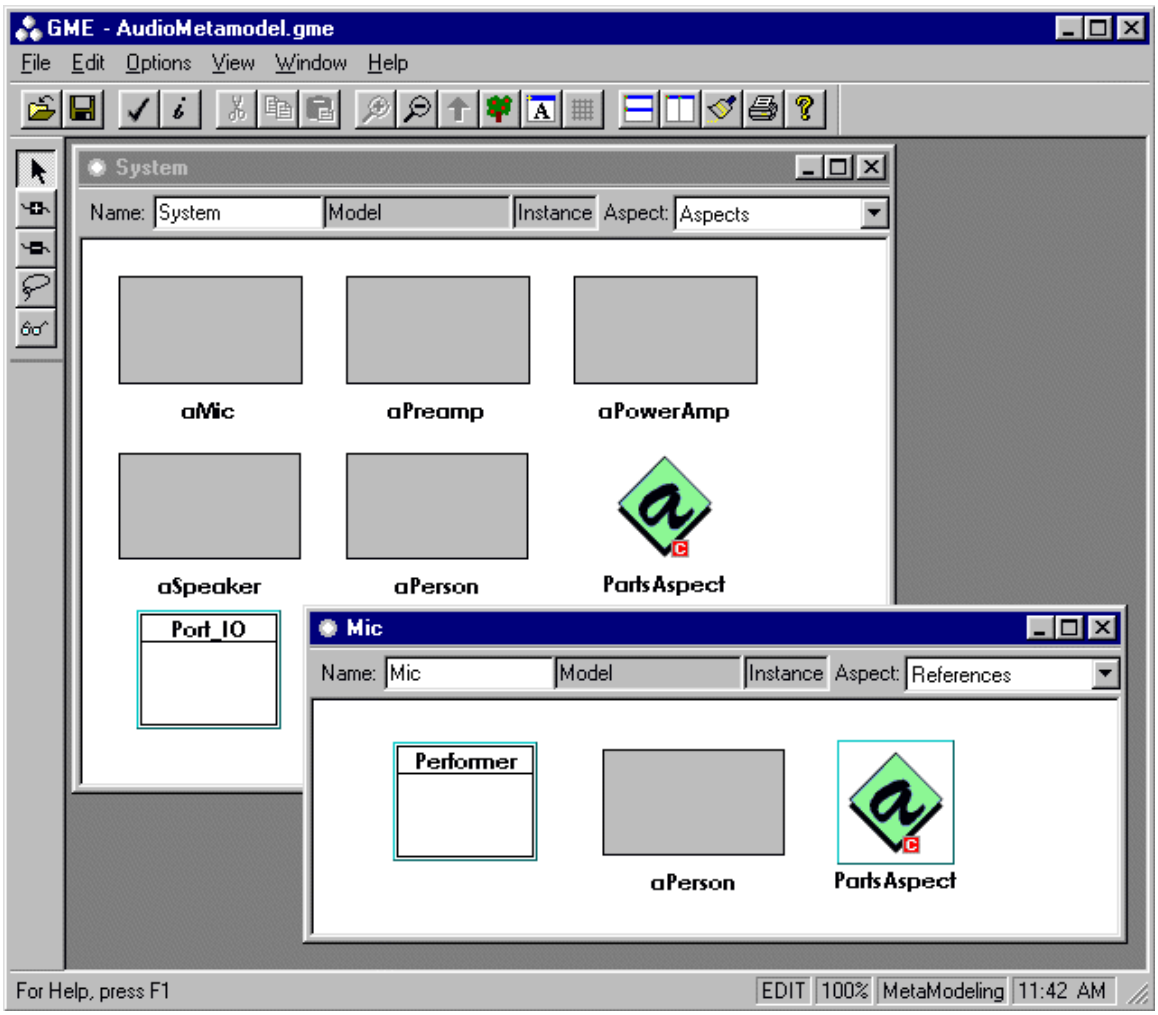


Figure 17: Mapping the Performer association into a GME reference relationship

Figure 17 shows how the Performer association is modeled as a GME reference relationship. Because the reference is contained in Mic, a copy of the Performer association class object is placed in the References aspect of the Mic model as shown. Also shown are a copy of an AtomicPart model named aPerson, and a copy of an aspect controller part named PartsAspect. (These are necessary since a GME part reference consists of the category, model, aspect, and name of the part being referred to, as well as a name for the reference part itself.) The reference name is taken from the copy of the

association class. To determine the model, a trace is made from the original UML association class object to object at the "dst" end of the association. That UML object represents the type (and thus, the name) of the model to use when constructing the GME reference.

Because aspects are a GME presentation feature, and not modeled in the UML diagram, a copy of the aspect definition *from the GME model where the reference source is located* must be included in the References aspect of the model containing the part reference. In Figure 17, this is indicated by the presence of the PartsAspect part, copied from the System model's Aspects aspect.

Next, the part type must be determined. Because the System model could contain several parts of type Person, a copy of the particular part being referred to (aPerson in this case) must be included in the Mic model's References aspect. The copy comes from the Aspects aspect of the GME model containing the referenced part. This is indicated in Figure 17 by the presence of the PartsAspect part, copied from the System model's Aspects aspect.

Finally, because a Model model may contain an arbitrary number of references (and thus an arbitrary number of copies of UML association class objects, parts, and aspects, all of which would appear in the model's References aspect), conditionalization is used to indicate the particular parts that constitute a given reference. The copy of the UML association class object is used as the conditionalization group's controller.

Figure 17 also demonstrates another metamodeling concept – object containment hierarchy. As shown in Figure 15, the System model is an aggregation of Mic, Preamp, PowerAmp, Speaker, and Person objects. This aggregation is modeled in the GME by

including copies of the Mic, Preamp, PowerAmp, Speaker, and Person models in the Parts aspect of the System model (the Parts aspect is not shown in Figure 17, but these parts are inherited by the Aspects aspect and are thus visible in the Aspects aspect).

In UML diagrams, association classes can act as the source of an association. Such associations are represented as "reference references" in the GME. Reference references are similar to part references, but a copy of the class object *from the model and aspect containing the original reference* is used instead of a copy of a GME AtomicPart model. An example of this is shown in Figure 18, where RefToPerformer (part of the Preamp model) represents a reference to the Performer reference contained in the PartsAspect of the Mic model. (Both Performer and PartsAspect were copied from the Aspects aspect of the Mic model, as shown in Figure 17.)

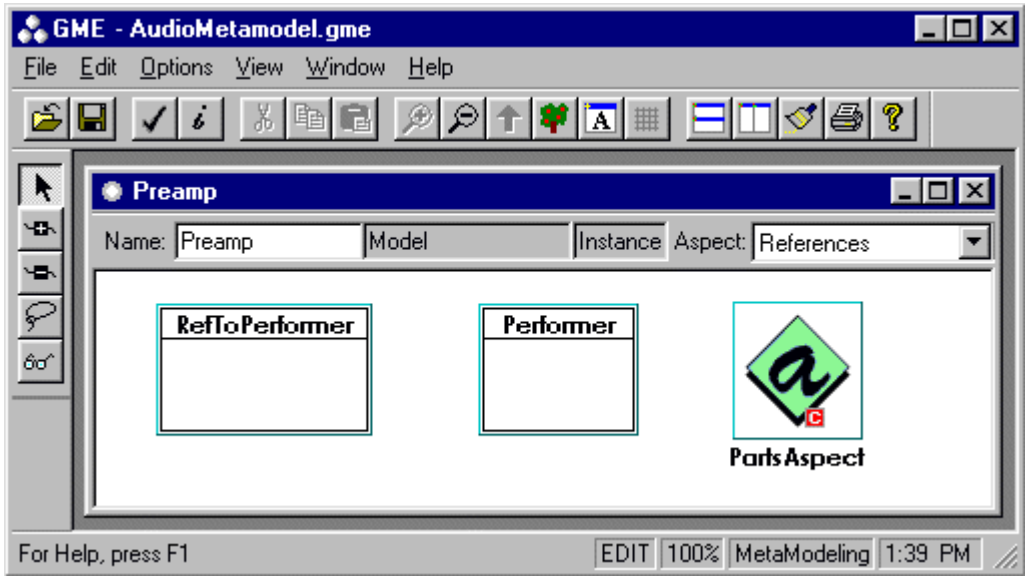


Figure 18: Modeling a reference to a reference

The final reference association shown in Figure 15 is the SoundSource association. In this case, SoundSource is used to indicate a Mic object reference contained within a Speaker object. As with earlier reference associations, the owner of the reference is the object at the "dst" end of the association. Because the UML Mic object maps to a GME Model model, SoundSource must be represented as a GME model reference. Figure 19 shows how this model reference relationship is modeled.

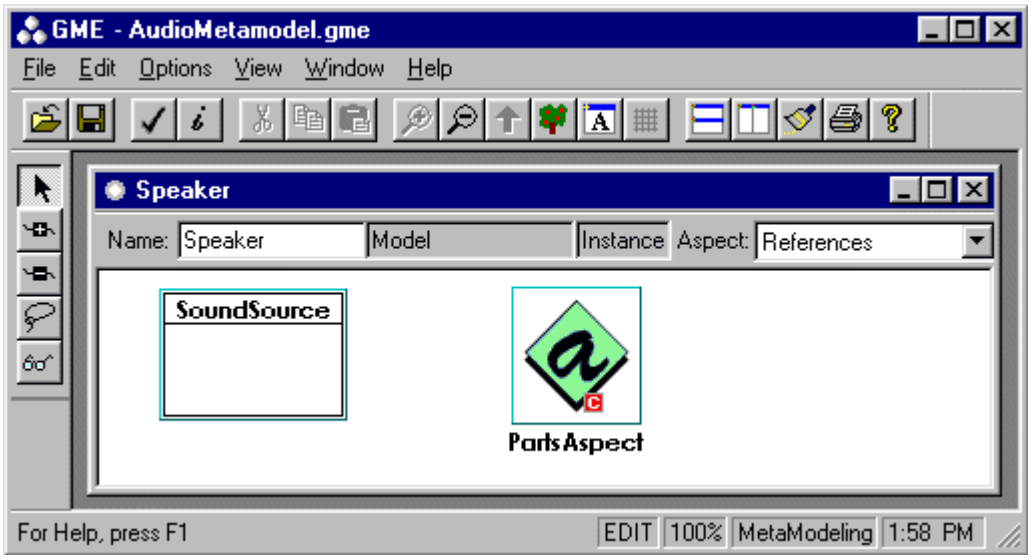


Figure 19: Modeling a model reference

A model reference is modeled in a manner similar to a part reference. Because the referenced object is a model and not a part or another reference, no copy of an AtomicPart model or UML class object is needed. However, as with the atomic part reference discussed above, a copy of the aspect controller part must be included when mapping an association class to a model reference.

Two final modeling concepts must be modeled – inheritance and conditionalization. Inheritance is always associated with the GME aspect mechanism.

Parts and connection groups are unique to a model, but many times they must appear in more than one aspect within a model. This behavior is modeled by creating an inherited conditionalization group in a model's Aspects aspect, and including that inherited group in one or more Aspect conditionalization groups.

Conditionalization as a GME modeling mechanism is modeled using conditionalization itself. A copy of the UML association class to be represented as conditionalization is placed in a model's Conditionalization aspect. The model's parts are also visible in the Conditionalization aspect. The copy of the UML association class acts as a conditional controller and is used to indicate which part will act as the modeled conditionalization group's controller. The GME part and connection objects belonging to the conditionalization group are determined during metamodel interpretation by examining the UML diagram to determine the types of objects being associated, finding the GME objects that these UML objects map onto, and creating a conditional group containing GME objects of those types. The ACME case study of Chapter IV demonstrates conditionalization modeling.

Discussion

To properly model all GME objects and features, an explicit mapping must be created between a UML diagram, representing the syntax of a target modeling environment, and various representations of the modeling resources available in the GME. This mapping is done by hand, and is performed by the metamodeler as part of the metamodel design process. By ensuring that all GME modeling facilities are able to be modeled, and properly constrained using various constraint equations, any type of GME modeling environment can be synthesized from a UML/GME metamodel.

CHAPTER IV

UML/GME METAMODELING ENVIRONMENT

Once a metamodel has been defined and used to synthesize a DMSE, domain experts can begin modeling specific systems within the domain. While such modeling activities are quite useful in their own right, the real power of a DSME is realized when domain models are *interpreted* using one or more semantic translators. The ability to scan the domain models, extract various kinds of data, analyze and translate the data, and synthesize executable models is the central feature of a DSME.

In the case of the UML/GME metamodeling environment, the semantic translators are used to extract information about the target DSME from the metamodel and synthesize the configuration files necessary to automatically generate the target modeling environment. This chapter discusses the UML/GME metamodeling environment, focusing specifically on the metamodel semantic translation process.

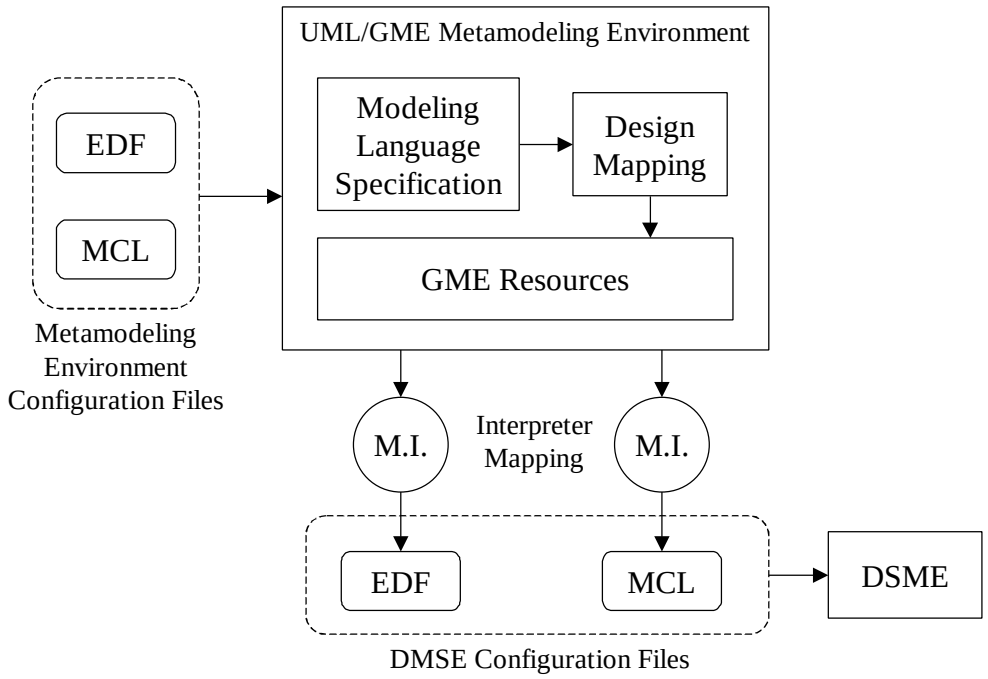


Figure 20: DSME generation

Figure 20 illustrates the overall flow of information and the necessary processing required to specify and generate a target DSME. The metamodeling configuration files (i.e. the EDF and MCL files shown on the upper left side of the diagram) are used to generate the UML/GME metamodeling environment. Initially these configuration files were built by hand, but as explained in Chapter V, Case Studies, a graphical meta-metamodel has been built using the UML/GME metamodeling environment that can generate these configuration files automatically.

Once created, the UML/GME metamodeling environment allows a designer to synthesize a DSME by (1) specifying the desired domain-specific modeling language, (2) specifying the mappings between the modeling language constructs and the various modeling services (i.e. resources) available in the GME, and (3) executing the semantic translators to automatically generate mappings between the metamodel and the target

DSME. These mappings take the form of the EDF and MCL configuration files shown near the bottom of Figure 20. The design mapping process was described in Chapter III. Here we will concentrate on the interpreter mapping portion of Figure 20.

Remember that the language specification, along with the design mappings, constitute the actual metamodel. When designing a DSME, once the design mapping phase is complete, model interpreters are used to synthesize the editor description file (EDF) and the MCL constraint equations from the metamodel. The DSME EDF and MCL configuration files are then used to automatically generate and configure the target DSME. The diagram of Figure 5 has been updated in Figure 21 below to reflect this modified DSME creation process. Note that when compared to the previous approach, this new method results in more of the target DSME being generated automatically, as well as providing features (e.g. constraint management) not previously available in the MGA.

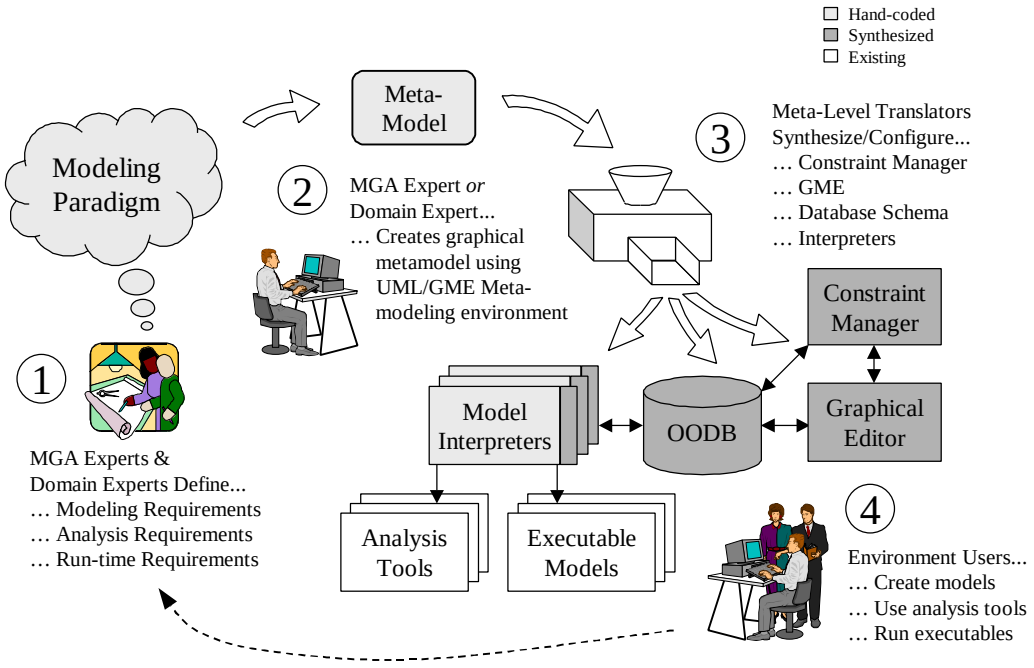


Figure 21: Creating a DSME using the UML/GME metamodeling environment

Metamodel Translation

As Figure 21 indicates, the metamodel translation process is responsible for configuring the constraint manager, the graphical editor, the model database, and the model interpreters. As mentioned earlier, automatic generation of model interpreters is the subject of ongoing research. The current UML/GME metamodel interpreter does not perform model interpreter synthesis or configuration.

Referring back to Figure 20, the model interpreters (M.I.s) create mappings from the language specification, represented as UML class- and constraint objects in the metamodel, and the design mappings onto the configuration space of the target DSME. In other words, the metamodel interpreters synthesize the EDF and MCL files from syntactic and semantic entity, relationship, and presentation information contained in the metamodel.

Once a particular metamodel has been created, metamodel translation begins with the creation of data structures corresponding to each UML class- and constraint object, as well as all GME modeling objects (e.g. atomic parts, models, references, attributes, connection- and conditionalization groups) and the presentation specifications (e.g. icon definitions, data structures representing the various aspects of a multi-aspect modeling paradigm, etc.) Once the data structures are created, they are traversed according to the associations and connections defined in the metamodel. Additionally, lists containing references to all atomic parts, model parts, connection groups, and conditionalization groups contained in each GME model object must be created and associated with each GME model object. By creating and initializing pointers between the data structures associated with UML and GME objects, a multigraph is formed that represents the metamodel specification.

Next, each node of the multigraph is visited, and new container data structures are created according to the types of objects represented by the nodes and edges of the multigraph. Data members of these container structures are then initialized using data from the node and edge objects. Object pointers are added to these container data structures and initialized to point to the other container structures as dictated by associations found in the multigraph.

The result of traversing this multigraph and creating a new set of linked container objects is a second multigraph that also represents the original metamodel, but containing model data and connection information necessary to *efficiently* build up the EDF and MCL files. (Efficiency is emphasized here since the data structures that form this second multigraph contain no new information – only the organization of that data has been

optimized to facilitate a rapid translation into the necessary target DSME configuration files.) Finally, the second multigraph is traversed and the EDF and MCL files are synthesized.

It is interesting to note that once metamodel interpretation has been completed, the newly generated DSME can be invoked *while keeping the first metamodeling environment open*. This allows the metamodeler to make changes to the metamodel, perform a metamodel translation, and immediately see the results of those changes reflected in the behavior of the generated target DSME.[8] This is especially helpful during the early stages of DSME design, allowing the rapid exploration and testing of alternative DSME designs and prototypes.

[8] Although two or more GME modeling environments may be open at once, changes in the target modeling environment will only take effect when the newly generated modeling paradigm is reloaded into the target GME. This is not the case with the newly generated MCL file, however. The target environment's constraint manager responds immediately to changes in the MCL file.

CHAPTER V

CASE STUDY

Representational Metamodels

In addition to the audio processing system described in the Metamodeling Process section of Chapter III, two other domain-specific modeling environments were created using the UML/GME metamodeling system as part of this research. Together, these metamodels demonstrate the full range and capability of the UML/GME metamodeling environment.

ACME

As discussed in Chapter II, ACME [9][10] is an Architectural Description Language (ADL) used to describe software systems. ACME uses *components* and *connectors* as basic architectural elements, both of which have interconnection interfaces. Component interfaces are called *ports*, and connector interfaces are called *roles*. Components and connectors are interconnected in a straight forward manner – component ports attach to connector roles, and connector roles attach to component ports – to form representations of software architectures. Groups of connections and components may be grouped together to form *attachment groups*. ACME use aggregations of components, connectors, and attachment groups to form *systems* – larger and more complex software representations.

ACME is a text-based ADL; no graphical specification for ACME exists. However, because the ACME metaphor of design is popular and well-known, a graphical

representation of the language would be of use to a large community of software system designers. For this reason, and ACME modeling environment was synthesized from a UML/GME metamodel. The UML portion from this metamodel is shown in Figure 22.

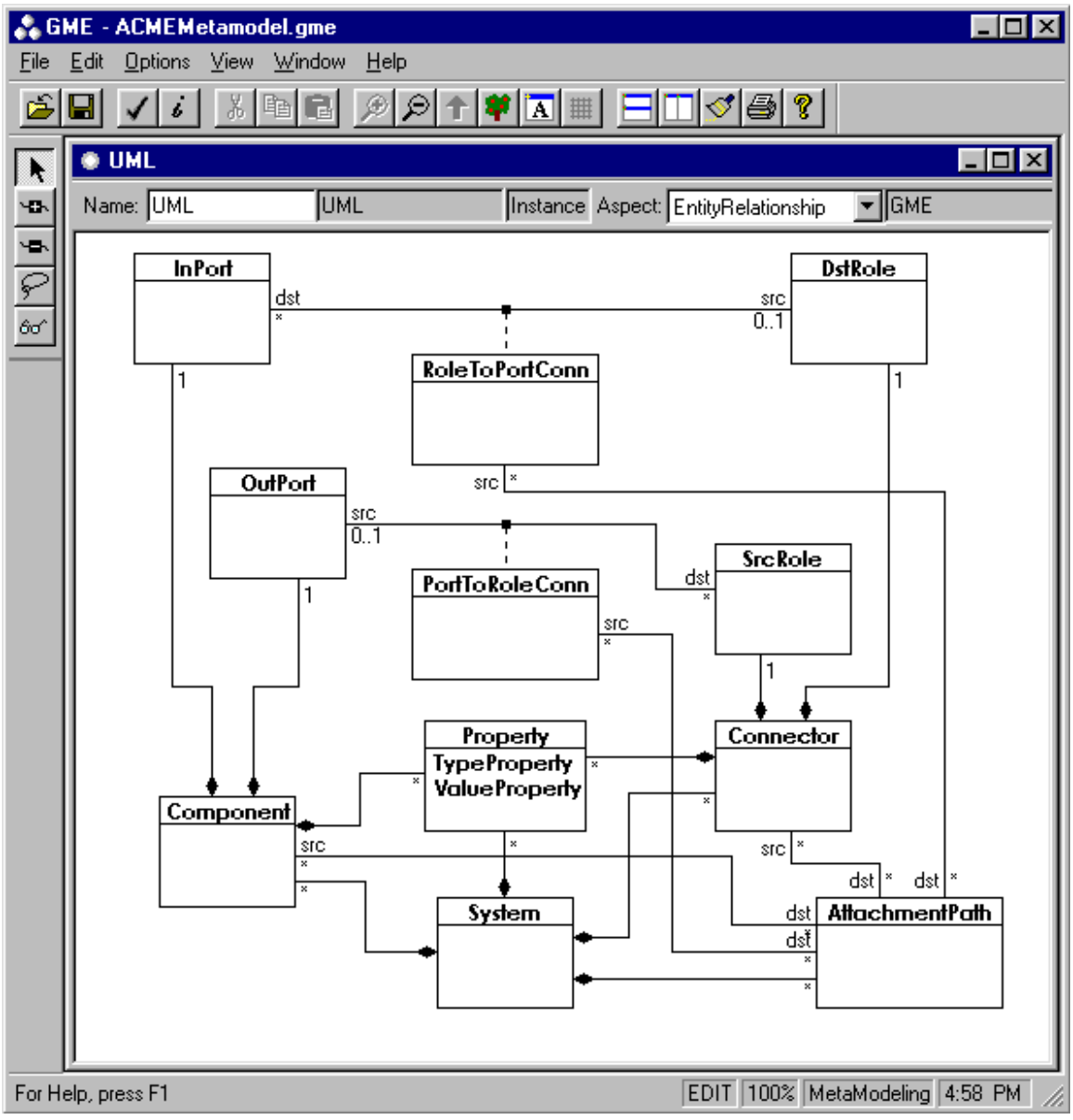


Figure 22: UML model of the ACME metamodel

Based on discussions in the Metamodeling Process section, it should be clear how most of the objects and associations in this UML diagram would be mapped to GME objects and relationships. InPort, OutPort, DstRole, and SrcRole objects map to GME AtomicPart models, while Component, Connector, and System objects map to GME Model models. RoleToPortConn and PortToRoleConn associations are represented as GME connection groups within the System model (since System contains both Component and Connector models). Property is an attribute associated with Component, Connector, and System models.

The UML AttachmentPath object is aggregated into the System object, and is associated with the Component and Connector objects, as well as the RoleToPortConn and PortToRoleConn association classes. AttachmentPath is used to represent groups of ACME components and connections between those components. Because components and connections are inherently different types of modeling objects in this paradigm, AttachmentPath is best represented in GME by conditionalization.

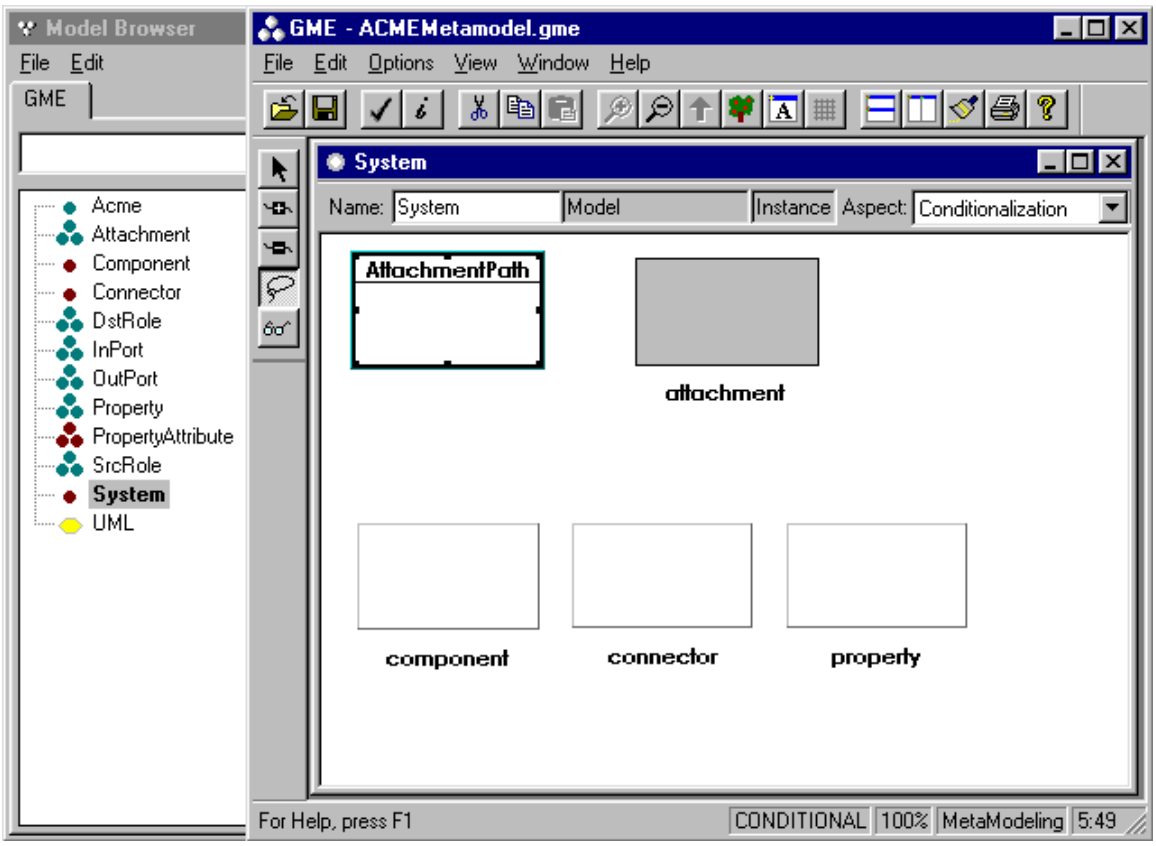


Figure 23: Mapping AttachmentPath to a GME conditionalization group

Figure 23 shows how the AttachmentPath is mapped to a GME conditional group. In addition to indicating which UML class object is being mapped to a GME conditional group, AttachmentPath acts as a conditional controller for the purposes of modeling this conditional group. In Figure 23, the editor is in conditionalization mode, as indicated by the depressed "lariat" button on the left side of the editor window. The AttachmentPath UML object is the controller of a group containing a single part – the "attachment" part (here, attachment is shown darkened in, while the component, connector, and property parts are shown only as outlines, indicating that they are not part of the group). By including attachment as a member of the AttachmentPath group, attachment is being identified as the conditional controller for the AttachmentPath conditionalization group in

the target environment. Note that no UML class object maps to this "attachment" part. Instead, a new GME AtomicPart model was created specifically as a controller part. This is necessary since conditionalization is a presentation mechanism unique to the GME – the UML diagram does not, and should not, contain "extra" objects only for use as presentation aids. Of course, any of the other parts contained in the System model (e.g. a component, a connector, or a property part) could have been selected as the conditional controller for the AttachmentPath conditional group.

Several semantic constraints are associated with this ACME modeling environment. Some, such as the multiplicity requirements on associations, are explicitly shown in the UML diagram of any metamodel. For example, Figure 22 indicates that a Component-type object must contain one InPort-type object and one OutPort-type object. Because the GME can only allow or disallow hierarchical "part-of" membership (i.e. parts are either allowed or not allowed to be contained within models), one or more constraints are necessary to ensure that the proper number of child parts are included in parent parts. Such constraints can be synthesized from the metamodel by the metamodel interpreter. In the case of Figure 22, the following constraint was synthesized to control the number of InPort objects that must be included in Component objects. Note that the metamodel interpreter synthesizes a similar constraint for every UML aggregation.

```
on demand_event
constraint SynthesizedConstraint0()
priority=0
"Every Component-type object must contain  exactly 1 InPort-type
object(s)" {
  models("Component")->forAll(model | (model.parts()->select(p |
p.kindOf()="InPort")->size() = 1))
}
```

In the case of constraints that are not stated explicitly in the UML, a constraint must be added to the metamodel. In the previous discussion of the GME/MCL metamodeling environment, such a constraint was shown in Figure 12. The UML/GME metamodeling environment uses a similar approach to specifying UML constraints. Regardless of whether the constraints are specified explicitly or synthesized from the UML diagram, the metamodel interpreter places such constraints in a configuration file for use by the CM in the target modeling environment.

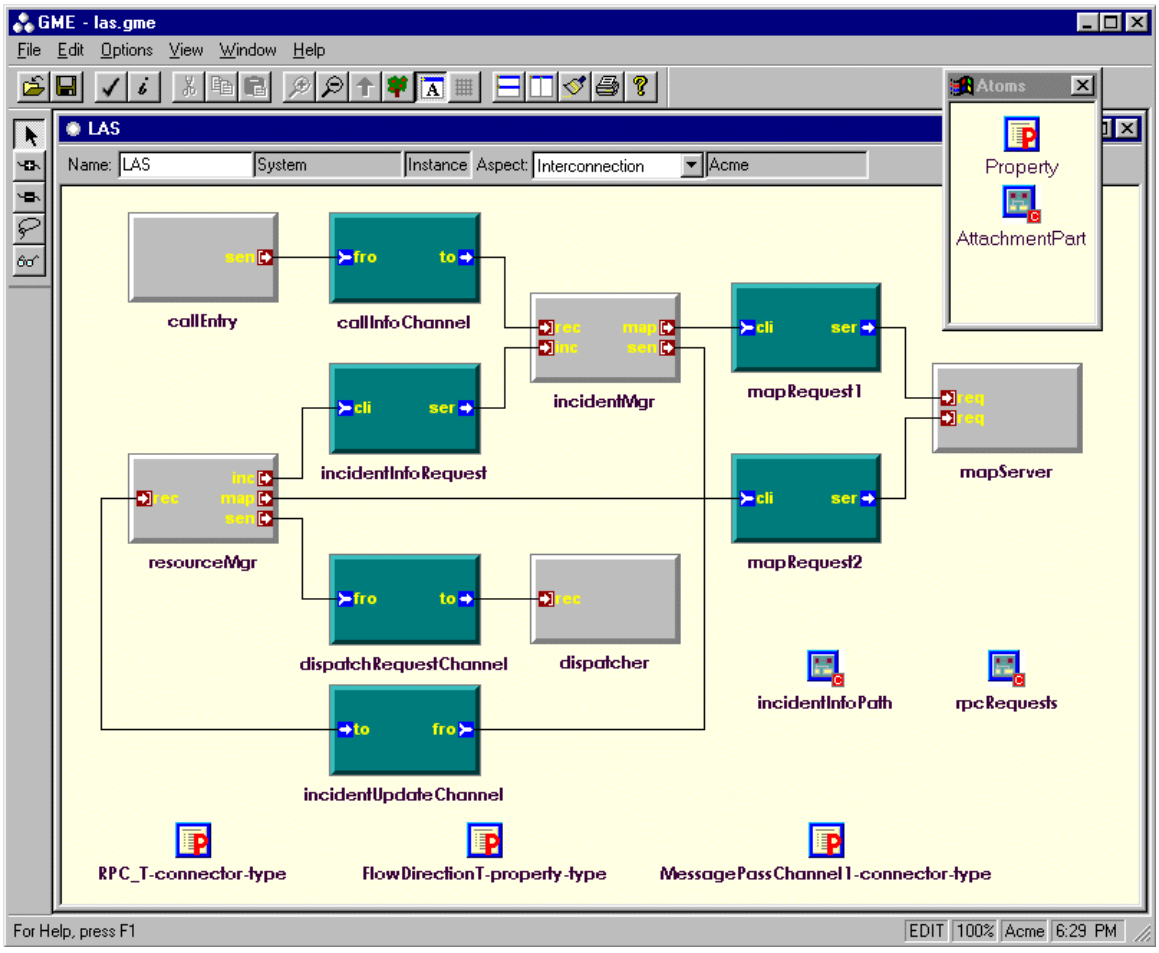


Figure 24: Using the synthesized ACME modeling environment

Figure 24 shows the synthesized ACME domain-specific modeling environment being used to model the proposed architecture for the London Ambulance System dispatch system (an example ACME model available in the "Samples" section of the ACME web site [10]). An interpreter capable of analyzing graphical ACME models and synthesizing textual ACME specifications was written for this ACME modeling environment. When executed on the model of Figure 24, the interpreter created a textual ACME representation semantically identical to that of the sample from the ACME web site.

Meta-Metamodel

As a final case study, a metamodel specification of the UML/GME metamodeling environment itself was developed. Such a metamodel is referred to as a meta-metamodel because of its self-describing nature. When the metamodel interpreter is used to synthesize a modeling environment from the meta-metamodel, the metamodeling environment that is generated contains all the features and behaviors of the UML/GME metamodeling environment that was used to create the meta-metamodel. In other words, the UML/GME metamodeling environment can be used to specify and build itself.

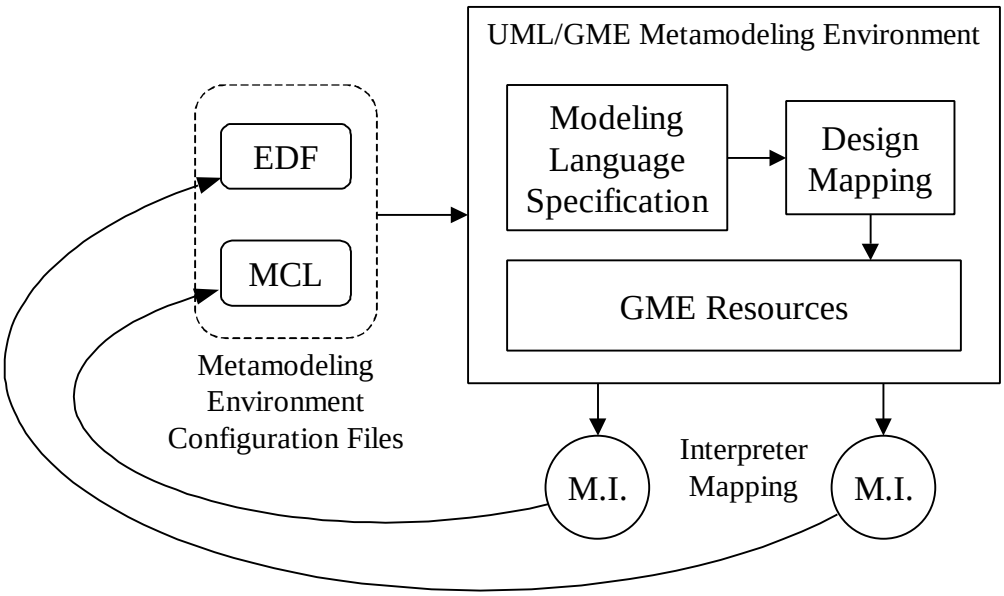


Figure 25: Using the UML/GME metamodeling environment to create itself

Figure 25 shows how the UML/GME metamodeling environment is used to describe itself. As with any metamodel, the model language specification and design mappings describe the objects, relationships, and behaviors of the desired target modeling environment. The only difference here is that the target environment being described is the UML/GME metamodeling environment itself. Once the design mapping phase is complete, the metamodel interpreter (note, this is exactly the same metamodel interpreter used in all previous examples) is executed, and the resulting EDF and MCL files are then used to generate a DSME – the UML/GME metamodeling environment.

Except for its size (it is rather large), the UML/GME meta-metamodel is constructed using the same techniques and facilities used in the previous two metamodeling examples, and contains no constructs not already discussed. Appendix D discusses the meta-metamodel UML class diagram, and so the details of UML/GME meta-metamodel construction will not be presented here. However, it is interesting to

compare the semantics of the UML modeling portion of the UML/GME meta-metamodel with the UML meta-metamodel presented in the UML Semantics document [3].

UML/GME Meta-Metamodel and UML Meta-Metamodel Comparison

UML contains many modeling features not used in the UML/GME metamodeling environment, such as state chart modeling, collaborations, use cases, etc., as well as many functions and operations on allowed modeling objects. However, the UML meta-metamodel defines a core set of object modeling features, many of which are used by the UML/GME metamodeling environment. To ensure compatibility with the UML standard, the UML modeling portion of the UML/GME metamodeling environment must have the same syntax and semantics as that found in a similar subset of UML.

Syntactic Comparison

Figure 26 shows the portion of the UML/GME meta-metamodel used to define the UML modeling objects and associations used in the UML/GME metamodeling environment. Direct comparison of this meta-metamodel with a suitably trimmed down portion the UML meta-metamodel reveals that both meta-metamodels define similar sets of core UML modeling objects.[9] Differences center around the need for a separate Aggregation association in the UML/GME meta-metamodel, due primarily to a lack of support for first-class association ends in the GME. Also, because the GME does not support attaching connections directly to other connections, a feature which is needed to

[9] Due to the size and complexity of UML, this comparison was performed using an appropriate subset of the UML meta-metamodel. Object hierarchy was flattened where possible, out-of-scope objects were omitted, and class object attributes were ignored.

add association class objects to associations, this type of relationship is modeled using the AssociationStart, AssociationEnd, AssociationClass, and the "A" object. "A" objects are mapped to small, square, black connector nodes in the GME. These connector nodes are used to create an association between three UML class objects – the source and destination of the association and the association class object.

Another difference between the UML/GME meta-metamodel and the UML meta-metamodel is the use of the "I" object in the UML/GME meta-metamodel to represent generalization (i.e. inheritance), with the BaseClass association representing the UML supertype association and the SubClass association representing the UML subtype association.

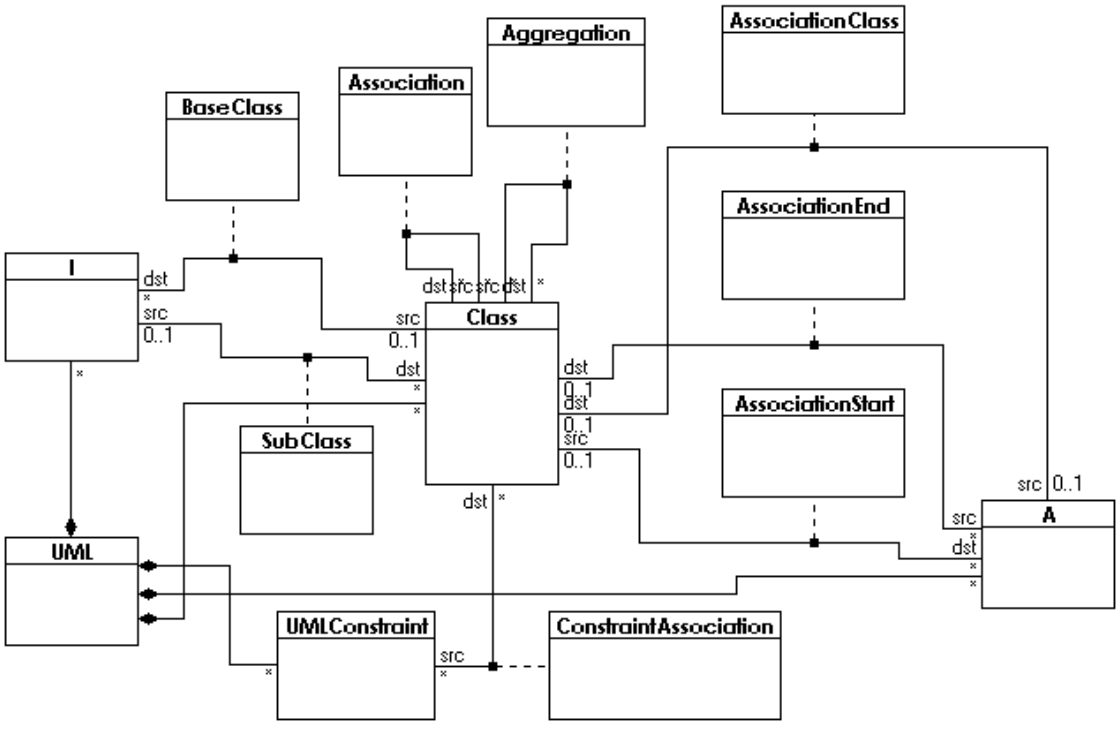


Figure 26: UML modeling portion of the UML/GME meta-metamodel

Semantic Comparison

UML meta-metamodel semantics are stated in [3] as a series of well-formedness rules associated with UML modeling objects and concepts, and are defined using a combination of OCL and standard English text. Because UML specifies no standard modeling environment when designing with UML, the creators of UML could not rely on any environment-specific editing mechanisms to enforce UML semantics. The result is a very complete and detailed set of semantic definitions for UML, devoid of all implementation and environmental detail.

However, because the UML/GME metamodeling environment is based on the GME, and is intended to create GME-based target DSMEs, the UML/GME meta-metamodel does not need to define as many semantic constraints as required in "pure" UML, but can instead make use of certain behaviors intrinsic to the GME. For example, the following UML meta-metamodel well-formedness rule (taken from [3], pg. 27) states that for any UML Association, at most one AssociationEnd of the Association may be an aggregation or composition:

```
self.allConnections->select(aggregation <> #none)->size <= 1
```

The UML/GME metamodeling environment also allows the use of association aggregation to specify containment, so the UML aggregation associations semantics must be expressed in the UML/GME metamodel as well. To achieve this, the Aggregation association shown in Figure 26 is mapped as a GME connection as shown in Figure 27 below.

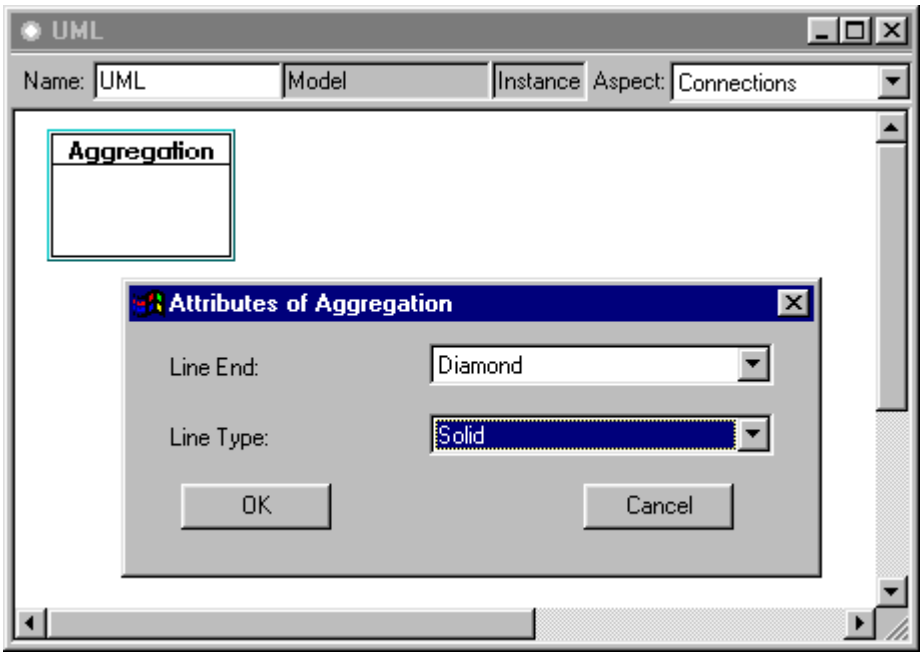


Figure 27: Aggregation mapping in the UML/GME meta-metamodel

As part of this mapping, the line end attribute is set as "Diamond," indicating an aggregation association. Because the GME meta-metamodel only defines the line end attribute for the "destination" end of an association, the GME intrinsically enforces the restriction that only one end of an association connection may be an aggregation indicator. It should be noted that this behavior is semantically correct and equivalent to the aggregation association semantics of the UML meta-metamodel, and is properly modeled in the UML/GME meta-metamodel. However, a separate MCL constraint expression was not necessary in this case.

While it is possible to "take advantage" of certain GME-specific modeling concepts when specifying semantic behavior in the UML modeling portion of the UML/GME meta-metamodel, this technique has been avoided whenever possible. A better approach is to define UML/GME metamodeling environment semantics using

MCL-based well-formedness rules similar to those found in UML whenever possible, relying on the GME constraint manager to verify the stated constraints. This approach provides a clearer separation of UML/GME metamodeling semantics in the meta-metamodel, and provides maximum design freedom and flexibility for the GME as it evolves over time (i.e. features will not have to be incorporated into the GME merely to support specific meta-metamodeling techniques).

This approach also allows many of the UML meta-metamodel well-formedness rules to be used directly to specify the UML modeling semantics of the UML/GME metamodeling environment, and still others to be used with only slight modification. However, because the GME inherently restricts how some modeling concepts are presented to the user, additional MCL constraints must be formulated to properly constrain any "alternative" notations used in the UML/GME meta-metamodel (such as the "A" objects of Figure 26) while maintaining a semantics consistent with the UML meta-metamodel.

To illustrate this, a total of fifteen constraint rules are necessary to properly define the UML object modeling semantics used in the UML/GME metamodeling environment. Of these fifteen, nine can be derived directly from the UML well-formedness rules in [3], three are inherently specified as part of the design mapping between UML and GME modeling objects within the UML/GME meta-metamodel, and three "new" MCL constraints are needed to support the alternative notation discussed above.

CHAPTER VI

RESULTS AND FUTURE WORK

Analysis of the UML/GME Metamodeling Environment

The UML/GME metamodeling environment allows the specification and synthesis of any GME-based target modeling environment. By properly separating modeling language syntax, semantics, and presentation requirements, the cognitive process of metamodel design is enhanced without unduly constraining the metamodeler. Users of this system have reported that the metamodeling paradigm is intuitive and easy to work with, being much less prone to error than previous text-based approaches to modeling environment specification and design. Also, because the UML/GME metamodeling environment has at its center the UML-based description of the target environment's objects and relationships, metamodelers were able to retain a consistent picture of the overall modeling environment being designed while concentrating on specific low-level language representation and modeling details. These observations are derived from exit interviews conducted with users of the system.

Novice metamodelers who had used the earlier OMT/GME-based metamodeling system reported that the UML/GME metamodeling environment was more intuitive and better suited to the design of DSMEs than the OMT/GME-based system. They noted that this was especially evident during the early phases of DSME design.

Capabilities

Because more and more computer- and software engineers are using UML to model computer based systems and languages, the use of UML in the UML/GME metamodeling environment enables the target modeling environment user to participate more fully in the DSME design process. Potential users familiar with UML but relatively new to the GME were able, with only a minimum of training, to specify DSME requirements using the UML/GME metamodeling environment. Of course, before being able to specify a complete metamodel, they needed to learn what types of resources were available in the GME, and had to become familiar with the graphical idioms used to specify the mapping between the UML and the GME modeling constructs.

While the text-based EDF does not allow hierarchical nesting of part- and aspect attributes, UML/GME metamodels do allow hierarchical aspect specifications (these are "flattened" by the metamodel interpreter during the EDF synthesis process). Also, part-to-part associations may be specified outside of a particular model's context – if either of the associated parts are contained in a model, all GME-mapped connections resulting from those part-to-part associations are synthesized hierarchically by the metamodel interpreter. Again, this amounts to a "flattening" of the design hierarchy.

As discussed earlier, the UML/GME metamodeling environment is self-describing, and can be used to model all modeling capabilities of the GME. Although still in the early stages of development, many DSMEs have been specified and synthesized using the UML/GME metamodeling environment.

The most significant improvement over other UML-based modeling systems is the ability to attach syntactic and semantic meaning to the metamodels, and to apply semantic translators (i.e. interpreters) to the metamodels, allowing automatic synthesis of

DSME's from the metamodels. And although synthesis of the semantic translators has not yet been realized, current research indicates this is both feasible and possible.

Regarding the use of UML and the OCL-based MCL constraint language to define the target modeling language syntax and semantics, it should be noted that the goal in developing the UML/GME metamodeling environment was not to duplicate all features of UML, nor to adhere to a strict realization of all UML object modeling syntax. Rather, this research sought to provide techniques and methods for DSME designers familiar with UML semantics to allow quick and accurate specification of modeling languages and DSMEs. Clearly that goal has been met.

Limitations and Restrictions

Although this research has led to several advances in DSME specification and synthesis capabilities, limitations still exist. Some of the more important limitation are addressed here.

The UML/GME metamodeling environment does not use UML class attribute information, but requires the metamodeler to create GME-based attribute specifications for inclusion in target modeling objects. This is due, in part, to the fact that UML class attributes are merely text strings, not as first-class modeling objects in the UML model. Consequently, UML class attributes are not inherited as specialized UML class objects are derived from more general ones.

As mentioned in the Capabilities section, part-to-part connections can be properly synthesized from UML containment specifications. However, currently only one level of connection inheritance hierarchy is supported. For example, if typeA parts can be connected to typeB parts, and one or more typeA parts are contained in a typeM model,

all possible connections between the typeA parts inside the typeM model and typeB parts located outside the typeM model will be synthesized by the metamodel interpreter. However, if a typeX model contains the typeM model, no connections will be synthesized from typeA parts contained inside the typeM model to any typeB parts that exist outside of the typeX model. What is needed is the ability for the interpreter to synthesize proper GME connections between parts separated by any level of object hierarchy, since many modeling paradigms require connections between parts located at various levels of hierarchy.

Another limitation relates to model size in the UML/GME metamodeling environment. As models grow large, the Windows-based GME editor creates "scrolling windows" that allow the metamodeler to view a model space larger than the screen. The GME attempts to mitigate this through a "zoom in/zoom out" mechanism. However, when zooming out, detail is lost as the individual models "shrink" in size to fit within the screen display. This limitation is compounded by the fact the UML is inherently a two-dimensional graphical notation, and no recommended method exists for organizing UML diagrams into groups of sub-diagrams. Metamodelers need larger and larger screens to see the overall design in detail. Although the separation of syntactic, semantic, and presentation requirements within the metamodel tends to partition the metamodel into smaller and more manageable pieces, the problem still exists. (One solution is discussed in the next section).

Finally, although a metamodeler can have both the metamodeling environment and the target modeling environment active at the same time, only the newly generated constraints are immediately available for use by the target DSME. A newly generated

modeling paradigm must be reloaded in the target DSME before the changes take effect. Changing the modeling paradigm in this way can result in invalid and/or unusable models. Currently no effective strategy exists for migrating models across modeling paradigms.

Recommendations for Future UML/GME Metamodeling Research

The research conducted as part of this dissertation only begins to explore the possibilities for DSME design and generation. As mentioned earlier, research is being conducted to add interpreter synthesis capabilities to the UML/GME metamodeling environment. Recommendations for additional research are made below.

MCL Expression "Helper"

MCL expressions are either synthesized automatically from the metamodel UML diagram, as in the case of connection multiplicity constraints, or they are explicitly supplied by the metamodeler. When stating constraints explicitly, the metamodeler provides the MCL expression as a simple text string. This is both time consuming and error prone, especially if some of the objects being referred to in the constraint are hidden in unopened models or are contained in aspects not currently visible to the metamodeler. Also, no syntax checking is performed during expression creation, and the environment provides no aid in constructing the constraint.

What is needed is some sort of automated helper – such as a Windows-based "Wizard" object – to guide the metamodeler during the creation of MCL expressions. The wizard should provide automatic or semi-automatic keyword recognition and/or selection, as well as real-time syntax checking.

Additional MCL Operations

This research has revealed the need for a more complete set of MCL operations and functions. A full set of end-to-end part connection functions are needed to simplify the specification of certain types of connections involving contained and inherited parts. Also, a function similar to the OCL "allSuperTypes" is needed to give access to an object's ancestors – necessary in order to properly guard against circular references.

Additional Constraint Synthesis

This research has demonstrated the ability to automatically synthesize MCL constraints from the UML/GME metamodel. Further research should be conducted on constraints common to all GME-based metamodeling environments to allow libraries of common constraints to be used to rapidly specify certain types of modeling environment behavior. Also, end-user should be able to define edit-time constraints – *ad hoc* constraints applied directly to the DSME by the modeler, *not* the metamodeler.

Model/Atomic Part Synthesis

Currently, some redundancy exists between the UML and GME sides of the metamodel. Class objects that aggregate other class objects and associations will clearly be mapped to GME Model models (since AtomicPart models cannot contain any objects). Similarly, UML class objects that are not used to aggregate other objects are likely to be mapped to GME AtomicPart models. However, creating the target GME Model- and AtomicPart objects, as well as specifying the UML-to-GME mapping, is done by hand, and as GME Model models are created, references to the AtomicPart models contained

within them must be explicitly placed inside the Model models – even though this containment has already been specified in the UML diagram. Mechanisms should be developed for automatic creation of contained part objects, and for establishing the necessary UML-to-GME mapping for these automatically created parts and models. Similar redundancy exists in the case of references and conditionalization.

UML Diagram Partitioning

As previously discussed, large UML diagrams can be difficult to manipulate and use in the UML/GME metamodeling environment. The UML/GME metamodeling paradigm should be extended to allow the UML diagram to be partitioned across multiple UML Model models. Any class object appearing in more than one of these UML Model models would be treated as the same object, regardless of where or how often it appears, allowing "layers" of UML sub-diagrams to be created. This layering of the UML diagram would allow the metamodeler to design and view relevant portions of the UML diagram without presenting him/her with unnecessary or out-of-scope information. This could also be used with the UML "design libraries" suggested earlier.

Appendix A

MODELING

This appendix is presented to familiarize readers with the terms and concepts that surround any discussion of metamodeling, and to ensure a proper context for a discussion of modeling in general. Many modeling terms and concepts are discussed, including modeling, modeling languages, model-integrated computing, and model-integrated program synthesis. All literature references in this Appendix are listed in the References section of the dissertation.

Modeling Languages

Modeling is the process of creating an abstract representation of an engineering system, and as such, modeling becomes a key strategy in the engineering design process. The artifacts of the modeling process are *models* – abstractions of the original system. As noted by Rumbaugh et al. [21], models serve several useful purposes:

- Testing a physical entity before building it
- Communicating with customers
- Visualization
- Reduction of complexity

While all of these purposes are important, perhaps the most important feature of a model is its ability to reduce the complexity of a design. Such abstraction enables a

clearer understanding of vital design elements and their relationships to each other, while allowing a designer to readily see how each element contributes to the overall design. Designing today's large software and hardware systems would be impossible without the ability to create and analyze models.

To aid designers in creating models of hardware and software systems, various modeling languages and systems have been created. For such modeling systems to be successful, they must be specific enough to allow designers to represent the key elements of various designs, without unduly constraining the designer, and yet remain general enough to allow a fairly wide variety of models to be created. Of course, some modeling languages are more suited to the task of hardware and software modeling that others. Some languages, such as ACME and C2, are oriented toward modeling software architectures, while others, such as Very High Speed Integrated Circuit (VHSIC) Hardware Description Language (VHDL), are more hardware oriented. Some modeling languages, such as the Unified Modeling Language (UML), seek to provide capabilities for modeling more complex systems that include both hardware and software. However, there can never be one, universal design language, since different designers, working in different domains, require design tools tailored to the domain at hand.

Before investing the time and effort required to exploit a modeling language, the language must be recognized as a standard, if not within the entire computer systems design community, then at least within the particular design domain of interest. Modeling languages that are considered standards (the term "standard" is used somewhat loosely here, since this is a relatively new field and new modeling languages are constantly being developed) have the ability to model entities, behaviors, and relationships in a number of

ways – usually driven by existing practice within a given discipline. For example, Harel's Statecharts [37][38] are a well known, often used method for describing the dynamic, interactive behavior of systems and subsystems. UML supports the use of statecharts (as well as other methods) for describing dynamic system behavior.

Another important aspect of modeling languages is the ability to adequately express common modeling concepts. Certain design requirements exist in many engineering disciplines, such as the need to represent the components in a system hierarchically, the need to associate certain objects with other objects (including the multiplicity of such associations), and the need to represent various relationships among objects. Similarly, a modeling language should support design component reuse. The use of standard templates and/or libraries of standard, parameterized design components representing these common modeling concepts ensures efficient and consistent models while minimizing design time.

Another desirable modeling language feature is multi-aspect modeling. Multi-aspect modeling refers to the ability to view a common, unified set of models from different perspectives or aspects. Subsystem designers need the ability to "filter out" parts of the overall system design that do not pertain directly to their subsystem, but to ensure that any interaction between subsystems is maintained when viewing the system as a whole. For example, consider a fly-by-wire flight control system. The system can be modeled using a unified model (perhaps a database) that contains all design information. However, portions of that unified model may be presented to subsystem designers in three distinct aspects – the hardware aspect, consisting of models representing the electrical and mechanical components of the flight control system; the software

architecture aspect, containing models of the various data structures and message passing facilities; and the control-law algorithm aspect, where the system's control feedback functions are modeled, possibly using math models. Each of these aspects may be considered separately when designing, analyzing and testing the system's various subsystems, but must be unified when performing analysis and testing the overall system model.

Coupled with the need for standardized modeling languages and language component reuse is the need for tools to support these languages. Designers must be able to rapidly prototype designs, refine and enhance their designs, integrate those designs with other design and analysis tools, and evolve their designs over time. A design environment can provide the designer with proper amounts of feedback regarding the use of the language, apply constraints prohibiting the designer from creating invalid models, and provide various mechanisms for using the models in support of larger design goals (e.g. simulation or safety analysis). Languages that are not supported by some sort of design infrastructure or design environment tend not to be very useful, and have little chance of being accepted as standards by the design community.

Once models have been created, the modeler must ensure that the models accurately reflect reality. This means the models must be both *valid* for the domain and *correct* in their representation of the key abstractions of the particular system they represent. Ensuring correctness is often a matter of inspection and testing. There is no easy formula that can be applied to a model to guarantee correctness. However, validity – the state of being a legal model that obeys the type and construction rules of the domain – is somewhat easier to check. One method is to use *formal methods* when creating the

models. Today, many formal languages exist that can be used to create models of domain-specific systems. Usually, these models take the form of formal *axioms* – often written in some form of predicate calculus – that describe key behaviors or relationships of entities in the models. Then, various *theorems* are created that also describe certain behaviors and relationships believed to be true. Finally, the modeler attempts to prove the validity of the theorems in terms of the axioms. Usually such proof strategies are performed using automated or semi-automated *proof checkers*. If the modeler has developed sound axioms and theorems, a formal proof gives a high degree of confidence in the model's validity. Two major drawbacks when using formal methods are (1) the need for highly specialized training in the use of formal methods, and (2) the lack of formal methods tools that can be easily integrated into a MIPS environment.

As mentioned above, many design scenarios can benefit from a simulation capability, if the particular modeling language being used can support such simulation activities. By allowing the modeler to simulate various static and dynamic conditions in the models, the designer can get a much better picture of the system's expected behavior, allowing designs to be analyzed, compared, and refined. These activities can range from a simple model translation capability, whereby models are transformed from one form to another more suitable for use by existing simulation tools, to a completely integrated simulation environment that allows the designer to design, analyze, and simulate various designs from within one integrated environment. Such integrated design and simulation environments provide more immediate feedback to the designer, allowing rapid model development and analysis, but can cause the design environment to be rather intolerant of changes in the modeling language itself.

Modeling has long been recognized as having many benefits. Simply performing the act of modeling often results in a more complete understanding of the system by its designers. This can be considered a passive form of knowledge acquisition on the part of the designer – more is known about the system as a result of the modeling process itself. Such gains in understanding are useful and not to be discounted. However, many times the designer creates models specifically to operate on them in some way, performing some sort of "what if" analysis, assigning an operational semantics to the models, or, in the case of executable models, incorporating execution semantics into the models. For example, if a designer is able to include execution semantics in the models of a production monitoring system in a manufacturing plant, the models could be used to control the production monitoring computers located on the manufacturing floor inside the plant.

One of the most important criteria in a modeling language is the ability to use the language to model itself. Changes to the modeling language will drive changes to any supporting design environment. If the modeling language has support for a meta-language, the language can be used to describe its own evolution. Combined with the ability to create executable models, such a modeling language can rapidly evolve as changes in modeling language requirements occur. By "modeling the modeling environment" or "modeling the models," the design environment can be quickly and safely evolved as time goes on. Meta-language support and metamodeling will be discussed in more detail in subsequent chapters.

To recap, there are several criteria for choosing a modeling language. These include

- the ability to model entities and to express relationships among entities,
- general modeling vs. domain-specific modeling,
- acceptance of the language as a standard,
- support for a variety of modeling techniques (e.g. state-charts, petri-nets, etc.)
- model composition and reuse,
- language extensibility,
- support for an automated design environment,
- ability to perform formal analysis of models,
- simulation capability,
- the ability to assign semantic meaning to models,
- the ability to create executable models, and
- meta-language support.

Of course, not all modeling languages support, nor need to support, all the criteria above. However, for the purposes of this dissertation, we will consider only languages that offer meta-language support. The need for such support is discussed in the chapter on metamodeling.

Model Integrated Computing

Model-integrated computing (MIC) is a methodology for generating application programs automatically from multi-aspect models. One approach to MIC is Model Integrated Program Synthesis, discussed below.

Model Integrated Program Synthesis

Model-integrated program synthesis (MIPS) is a method for allowing experts in a particular domain to create an integrated set of models representing all or part of various domain-specific systems, then using those models as a basis for analysis of, interaction with, or to automatically generate programs for the actual system. A MIPS environment consists of three main components: (1) a domain-aware model builder, used to create and modify models of domain-specific systems, (2) the models created using the model builder, and (3) one or more model interpreters, used to extract and translate semantic knowledge from the models.

A MIPS environment operates according to a modeling *paradigm*. A modeling paradigm is a set of requirements that governs how systems within the domain are to be modeled. For a given domain, a modeling paradigm answers such questions as:

- "What key entities and relationships from the domain must be represented?"
- "What modeling language should be used for modeling?"
- "How best to use the modeling language to represent the key entities and relationships?"
- "How can domain semantics be represented by the models?"
- "Once represented, how can the semantics be extracted from the models?"
- "What analysis must be performed on the models?"
- "What run-time requirements exist for any generated executable models?"

Typically, MIPS experts will not have the answers to such questions, but must work with domain experts to formulate the final modeling paradigm. Once the modeling

paradigm has been established, the MIPS expert can create a domain-specific model builder and any required model interpreters. Note that an important criteria when selecting a MIPS environment is the speed with which the model builder and interpreters can be created once the modeling paradigm has been established. Each of the key MIPS components are examined in some detail below.

Model Builder

The model builder is the primary interface between the domain expert and the MIPS environment. The model builder must allow the domain expert to describe systems from the domain in a fashion familiar to the modeler. In other words, the "language" of the model builder should be familiar to the domain expert. For example, when creating models of digital signal processing systems, the domain expert expects to work with entities such as microprocessors, buffers, I/O connectors, DSP algorithm blocks, etc. The expert relies on the model builder to *allow* certain actions, such as connecting processors to data buses, and to *disallow* other actions, such as connecting two output ports together. Therefore, the model builder must be aware of the construction semantics for the domain, and must be able to monitor the user's actions as models are created. The domain expert must have confidence that the model builder will not allow invalid domain models to be created. Note that the process of ensuring that only valid models are created is not a trivial problem. Objects created in one aspect of a multi-aspect model builder may drive the placement or use of objects in other aspects. Also, models may be valid within each aspect, but may be invalid when considered as a whole. For example, consider the "hidden loop" problem. Here, the model builder must prevent the possibility of a loop

being created by the aggregation of several acyclic sub-models. A variation of this is the case where certain relationships (i.e. *connections*) among objects in one aspect require (or restrict) certain relationships in other aspects – relationships that may be legal in the context of one particular aspect, but illegal when the model is considered as a whole.

In addition to ensuring proper model construction, the model builder must be able to save and retrieve models from some persistent storage medium. Also, the model builder should allow models to be saved in various forms, allowing models to be shared by various modeling environments. A simple example would be the storage of models as *objects* in an object-oriented database, but also allowing a *textual* representation (i.e. a text dump) of the models for use by other applications, such as a text editor.

Models

As mentioned above, domain experts create domain-specific models using the model builder. Because these models capture key semantic information about actual systems, the models must be able to hold all the necessary information while conveying proper meaning to the modeler. Factors such as element size and placement, coloring, information hiding, etc. must be considered when creating models. Also, the modeler must have an understanding of how the model interpreters (discussed next) will operate on the models. Said another way, the modeler must be aware of the modeling paradigm so as to create *meaningful* models.

Model Interpreters

Perhaps the most important components of any MIPS environment are the model interpreters. Model interpreters do much of the "work" of the MIPS environment, acting as semantic translators, allowing the information contained in the models to be used for a variety of purposes.

Model interpreters can act simply as translators, transforming the data contained in the models into other forms – forms more suitable for use by existing analysis tools. In other cases, the model interpreters can perform the analysis themselves, providing results to the modeler and/or other computer-based applications.

One of the most powerful uses of model interpreters is to perform *model interpretation* – synthesizing executable models (i.e. executable code) from domain models. Source code, in a variety of languages and formats, can be generated automatically, creating executable models that can be used to perform various calculations and operations while the actual domain-specific system is operating. For example, a MIPS environment can be created for modeling the data acquisition and analysis functions of various computerized monitoring stations located on the production floor of a manufacturing facility. Model interpreters would be used to synthesize the actual executable code to be used on each of the monitoring stations from models representing the plant's current configuration. Additionally, if the delivery of the executable code via some intra-plant network is modeled, the interpreters can generate code that will automatically download and execute the monitoring code on each of the monitoring computers in the plant.

Appendix B

FORMAL METHODS

Formal Methods (FM) consist of a set of techniques and tools based on mathematical modeling and formal logic that are used to specify and verify requirements and designs for computer systems and software [39]. The goals of FM are to reduce the overall cost of software development by reducing software design and requirements defects through a mathematical process of software verification and validation. While many approaches to FM exist, all are based on formal specification and verification of software through the use of theorem proving.

Formal Specification

A model is said to be *valid* (or *legal*) if it conforms to a given model construction semantics specified in a modeling paradigm. A model is *correct* if it faithfully represents reality. Assuming that the modeling paradigm itself is correct, we can then state that all correct models are valid models. However, the converse may not be true – valid models are not necessarily correct models. For example, imagine that an existing power plant is being modeled, but the modeler fails to include a critical plant component, such as an over-current detector. In this case, the model is valid (the modeling paradigm does not *require* over-current detectors, but merely *allows* them), but incorrect – it does not represent reality. However, if the modeling paradigm required every model to include the over-current detector, the model would be invalid.

Why draw such a distinction? Only by reasoning about a particular domain model in light of a consistent metamodel can the domain model's validity be determined. And while such reasoning can be done mentally for relatively simple metamodels, as the size and complexity of the modeling paradigm grows, the metamodeler cannot be expected to validate a metamodel's consistency by mental reasoning alone. If, however, the metamodel is expressed in a formal specification language, the metamodeler can employ a computer to aid in the task of ensuring metamodel consistency[10]. Today's popular FM languages are based on first-order (or higher) predicate calculus.

Another aspect of formal specification is the ability to "under specify" a system. The specifier need not state or even know the implementation details of a design to apply FM. Abstracting out key elements of the design, and performing FM on those elements often reveals top-level flaws in the system design.

The next question becomes "which formal language to use?" The answer depends on the goals of the metamodeling activity. In the case of the MGA, there are four main goals driving the move toward metamodeling.

First, the formal language must be able to represent the types of constraints that the metamodeler expects to encounter. In the case of OMT [21], the modeler is faced with a finite set of possibilities. Only so much can be represented using OMT, and no facility exists for the modeler to extend OMT to cover new situations. Thus, graphical modeling "standards" such as OMT or UML [22] are not adequate for describing the modeling relationships found in typical MGA applications. A better choice in this case is

[10] Consistent metamodels will lead to modeling environments which are *better able* to prevent a system modeler from building invalid, if not incorrect, models. Inconsistent meta-models will almost certainly lead to incorrect models!

one of the many programmable formal specification languages, such as Specware [30][31], Larch [32], or PVS [40].

Second, metamodels must be able to be assembled from general, pre-existing specifications of model composition constraints. The metamodeler must be able to easily combine specifications to form a metamodel that accurately reflects the requirements represented in the modeling paradigm. Therefore, the formal language must have mechanisms for combining one specification with another, and for customizing or refining the specification from a general form to a more domain-specific form. A few FM languages have at least a partial capability of creating and refining specifications from existing ones, notably Specware, Larch, and PVS. Specware has by far the most support for refining abstract specifications into more concrete (and, therefore, domain-specific) specifications.

Third, because the metamodeler will use computers to aid in checking model consistency, the formal language must support a theorem prover. Once the modeler believes the metamodel contains the proper axioms describing the modeling paradigm, theorems must be developed by which to test the metamodel. Only then will the metamodeler have sufficient confidence in the metamodel to use it to create a MIPS environment.

Finally, because the MIPS environment will be synthesized from the metamodel, the metamodeler must be able to transform the metamodel into a form suitable for use by the MGA. Therefore, the formal language must be an open language, supporting access to its internal data structures, so that key pieces of information may be extracted and used in the transformation process.

Formal Verification

Once a formal specification has been written, it must be verified. Formal specifications are verified by taking selected invariant expressions in the specification, casting them as *axioms* in the calculus they represent, then creating various *theorems* that are then proved correct (or incorrect) using a supported theorem prover. Note that no sort of *absolute verification* is possible using this approach, but only a *relative verification*. FM make it possible to calculate whether a certain system description is internally consistent, whether certain properties are consequences of proposed requirements, or whether requirements have been interpreted correctly in the derivation of a design [39]. Note, however, the act of verification is very beneficial to the design process, revealing design flaws that would likely go otherwise unnoticed (especially in the case of misinterpreted specifications). Therefore, formal verification can provide a high degree of confidence in a specific design, and more confidence in the overall system specification.

Theorem Proving

As mentioned above, formal verification is accomplished by assuming certain design requirement specifications to be axioms, then creating theorems from those axioms, and attempting to prove the theorems correct using the axioms as a representation of "ultimate truth" about the specification. Although theorem proving has been around for many years, there is no single best approach. Theorem proving can always be done with pencil and paper, following the rules of proofs from first-order

predicate calculus. However, recent advances in computer-aided theorem proving have greatly reduced the tedium of theorem proving, while providing a checkable "trail" of the steps involved in the proof itself.

No "completely automatic" theorem prover exists. Today's theorem provers are actually "proof assistants" [32], providing aid in debugging formal specifications. Such help comes in the form of redundant conjectures (i.e. additional theories) about the specifications, as well as providing the ability to "remember" old proofs and recheck them in light of modified theories. However, as helpful as today's theorem provers are, the process of theorem proving can still be tedious, and can end up revealing little new insight into a design. Because of this, the trend in theorem proving has moved away from attempting to specify and carry out a complete proof on an entire software system, moving instead toward specifying and proving only critical portions of a software system.

Appendix C

META-INTERPRETER ALGORITHM

As discussed in this dissertation, once a metamodel has been created, a meta-interpreter is used perform various semantic translations on data contained in the metamodel. The output of this semantic translation process are GME configuration files (the EDF and MCL files) that are later used to "customize" the GME for a particular domain. This appendix describes, using pseudo-code and plain-text English, the high-level algorithm used to perform this meta-translation.

Data Structure Creation and Initialization – Phase I

The algorithm begins by creating data structures that, when initialized, form a multigraph representing all modeling objects in the metamodel. Each data structure contains lists of connected objects, referenced objects, and conditionalization groups that the particular object is a member of. Additionally, the values of any attributes associated with each object are read and stored in the object's data structure.

```
forall class objects in the UML model
  establish pointers to parent, child, sub- and super-type objects
  establish pointers to associated GME models
  initialize attribute variables associated with UML class object
forall GME Paradigm, Attribute, Model and AtomicPart models
  establish pointers to associated GME objects
  establish pointers to associated UML class objects
  initialize attribute variables associated with GME object
```

Data Structure Creation and Initialization – Phase II

Next, the newly formed multigraph is traversed by visiting each node. During this traversal, a second set of linked data structures are created and initialized using values contained at the nodes of the first multigraph. This second multigraph is organized to facilitate the efficient synthesis of the necessary EDF and MCL files. The processing algorithms required to initialize these data structures and form the second multigraph are outlined in pseudo-code below. A textual explanation follows the pseudo-code.

```
forall GME models
  if model is of type "Paradigm"
    create a Categories list
    for each Category model contained in the Paradigm model
      add to Categories list
      create a Models list
      for each Model model contained in the Category model
        add to Models list
        create a Parts list
        create a References list
        create a Connections list
        create a Conditionals list
        create an Aspects list
        for each GME part in the Parts aspect
          if an atomic part
            create a new Part data structure – add to Parts list
            initialize Part attribute values
            initialize pointer from Part to parent (Model)
            initialize pointer in parent (Model) to Part
        for each UML reference in the Connections aspect
          create a new Connection object – add to Connections list
          determine UML objects at src, dst ends of association
          create list of GME parts of UML src type in this Model
          for each GME src type object
            create list of GME parts of UML dst type in this Model
        for each UML reference in the References aspect
          create a new Reference object – add to References list
          determine UML object at src end of association
          set ref part name from GME part in References aspect
          set ref aspect name from GME aspect part in References aspect
          set ref model name from current Model
        for each UML reference in the Conditionalizations aspect
          create a new Conditionalization object – add to Cond. list
          for each connected UML src object
            if UML object is associated with a GME part
              add part name to list of conditionalized parts
            if UML object is associated with a GME connection group
              add part name to list of conditionalized connections
```

```
          for each Aspect part in the Aspects aspect
            create a new Aspect object – add to Aspects list
            determine conditionalized parts associated with Aspect part
            if Inherited part type
              get list of inherited parts associated with Inherited part
              add all inherited parts to this aspect's parts list
            else
              add part to this aspect's part list

forall UML Constraint objects
  create a constraint data structure
  initialize structure with attribute data from UML Constraint object
```

This algorithm locates all Model models contained in each Category model which are subsequently located inside Paradigm-type models. The various aspects of each Model model (e.g. Parts, Connections, References, Conditionalizations, and Aspects) are examined. Links back to the UML model are used to determine, from the UML Entity-Relationship model, which UML class objects are associated with the UML class object that appeared in the GME model. These UML associations are then used to determine, via references from the UML model back to the GME models, which GME objects (of the proper type) are allowed in the various GME relationships that are represented by UML references in the GME Model's aspects (remember, the UML associations are mapped onto the GME relationships by placing reference copies of UML objects into various aspects of GME Model models). This information is then used to initialize various lists contained in the data structures representing the GME modeling objects. Last, all UML Constraint objects are found, and attribute data is extracted and used to initialize a constraint data structure.

EDF, MCL synthesis

Once the various data structures representing the various GME modeling objects are initialized as shown above, they are traversed and the data used to synthesize the EDF and MCL files, as described in the algorithm below.

```
create an empty EDF file
use data from Paradigm model to write a paradigm spec to file
forall AtomicPart data structures
  write atom header to file
  use data in structure to write an EDF atom spec to file
forall Model data structures
  write model header to file
  for each Aspect data structure
    write aspect header to file
    write conds section header to file
      use data in structure to write an EDF conditional spec to file
    write conns section header to file
      use data in structure to write an EDF connection spec to file
    write parts section header to file
      use data in structure to write an EDF part spec to file
      use data in structure to write an EDF reference part spec to file
forall Category data structures
  write category header to file
  use list of models in Category structure to write category spec

create an empty MCL file
write MCL header info
forall constraint data structure objects
  use data in structure to write an MCL constraint spec to file
```

Appendix D

THE UML/GME META-METAMODEL

The UML/GME meta-metamodel is a complete description of the UML/GME metamodeling environment. When the meta-interpreter is used to perform a semantic translation on the meta-metamodel, the result is a set of configuration files that can be used to configure the GME to perform metamodeling. In other words, the UML/GME metamodeling environment is self describing – it is capable of boot-strapping itself and participating in its own evolution.

The UML/GME meta-metamodel was presented in Chapter V as a metamodeling technology case study. In that study, the UML/GME meta-metamodel was compared with the meta-metamodel used to describe the UML modeling language itself. It was noted that, with a few exceptions related to implementing UML modeling concepts using the GME environment, the UML/GME meta-metamodel has the same semantics as the object modeling portion of the UML meta-metamodel. However, the case study did not discuss other aspects of the UML/GME meta-metamodel. They are discussed below.

Specifying UML and Constraint Objects

As mentioned above, the UML object modeling portion of the UML/GME meta-metamodel has the same semantics as the object modeling portion of the UML meta-metamodel. For reference and as an aid to further discussions in this appendix, object modeling portion of the UML/GME meta-metamodel is presented in Figure 28 below.

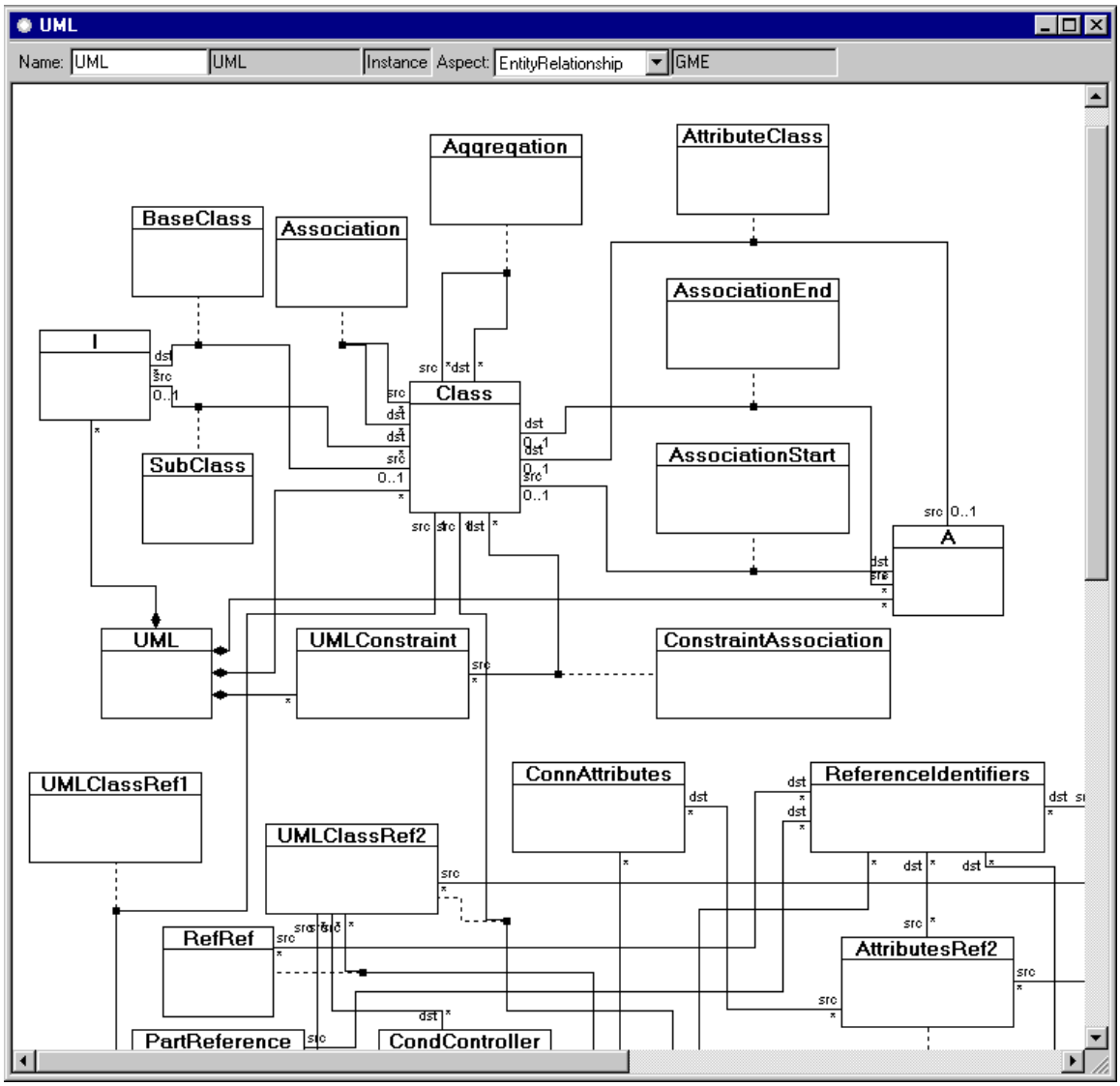


Figure 28: UML/GME Meta-metamodel showing UML object modeling specifications

UML/GME Object Modeling Specification

The UML specification for the GME "Model" object is shown in Figure 29 below. One of the most complicated GME modeling objects, the Model can contain atomic parts, other model parts, part references, connections, and conditionalized groups of parts and connections.

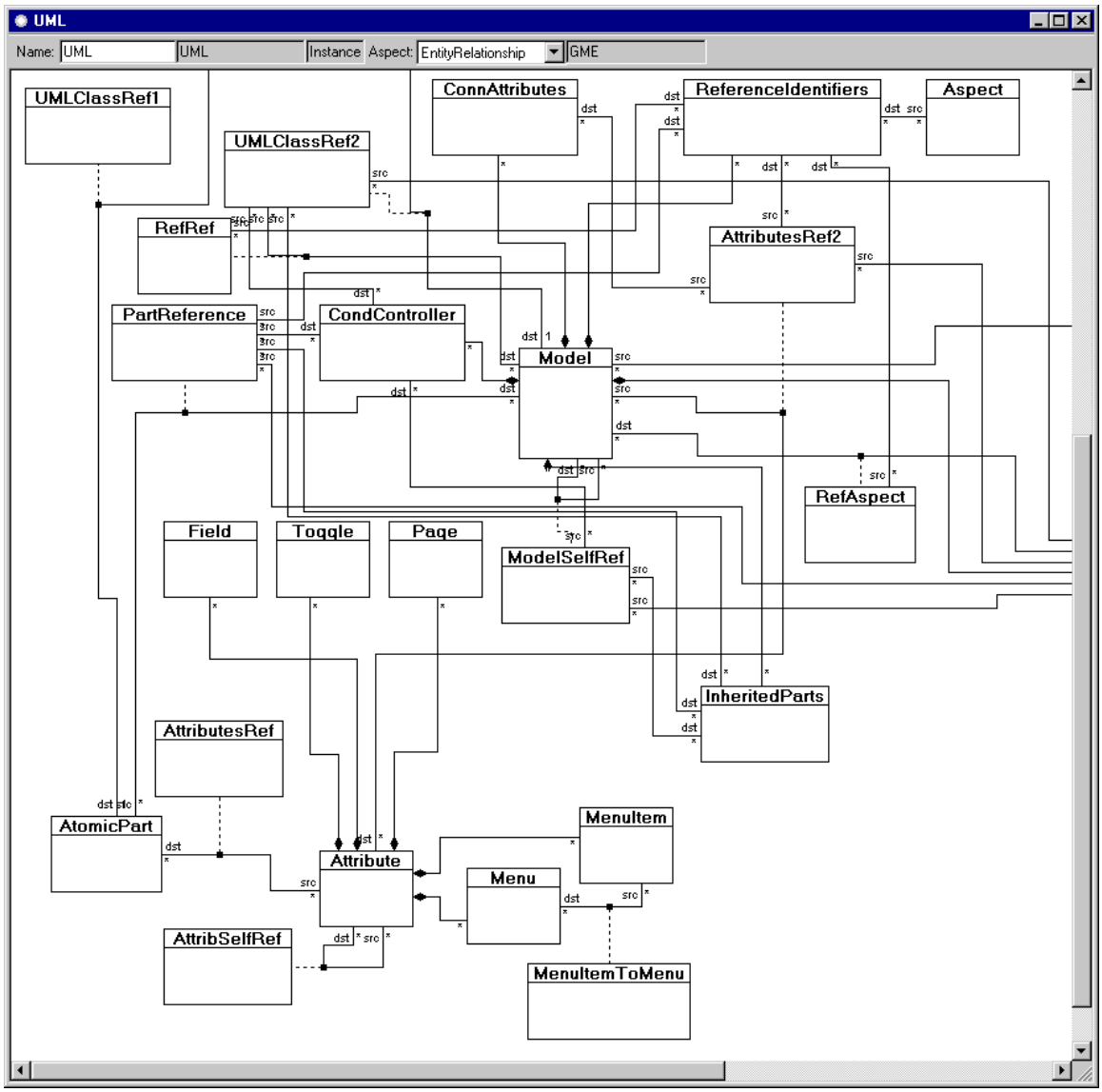


Figure 29: Specifying the GME Model modeling object

The meta-metamodel specification of a GME Model contains certain parts which represent the various association mappings used to map UML associations onto GME presentation specifications. These mappings are represented in Figure 29 as references to UML class objects (UMLClassRef2), references to Parts (PartReference), references to other Model objects (ModelSelfRef), references to Aspects (RefAspect), and references to various Attribute models (AttributeRef2). Remember that GME modeling objects (e.g.

AtomicParts, Models, etc.) are partitioned into aspects within a Model, and the same object may appear in more than one aspect. As such, all modeling parts have a primary aspect associated with them (where the part's "ownership" by the Model is first declared) and one or more inherited aspects. Thus, inherited parts have a special association with Models, similar but distinct from the association between Models and non-inherited parts. This special association is specified by the InheritedParts UML class object of Figure 29.

Specifying GME Attributes

The GME allows various types of attributes to be created and associated with atomic parts, models, part- and model references, connections, and aspects. Attributes may be represented in the GME using several forms, such as menus, textual fields, or Boolean "toggle" buttons. Attributes are modeled in metamodels using a hierarchical approach (i.e. attributes are defined once and may then be used to define other attributes).

Figure 30 shows how attributes are specified in the UML/GME meta-metamodel. The specification is straight-forward. Attributes are aggregations of the various design elements just discussed, as represented by the Field, Toggle, Page, Menu, and MenuItem class objects. MenuItems have a special association with Menus (menus are comprised of menu items) as expressed by the MenuItemToMenu association class. Also, the AttribSelfRef association allows attributes to be included in the definition of other attributes. This association is not mere aggregation, but will be represented in the GME by referential copying of previously constructed attributes. As such, the AttribSelfRef will be mapped to a GME object reference relationship, not an object containment relationship, during the presentation specification phase of meta-metamodel construction.

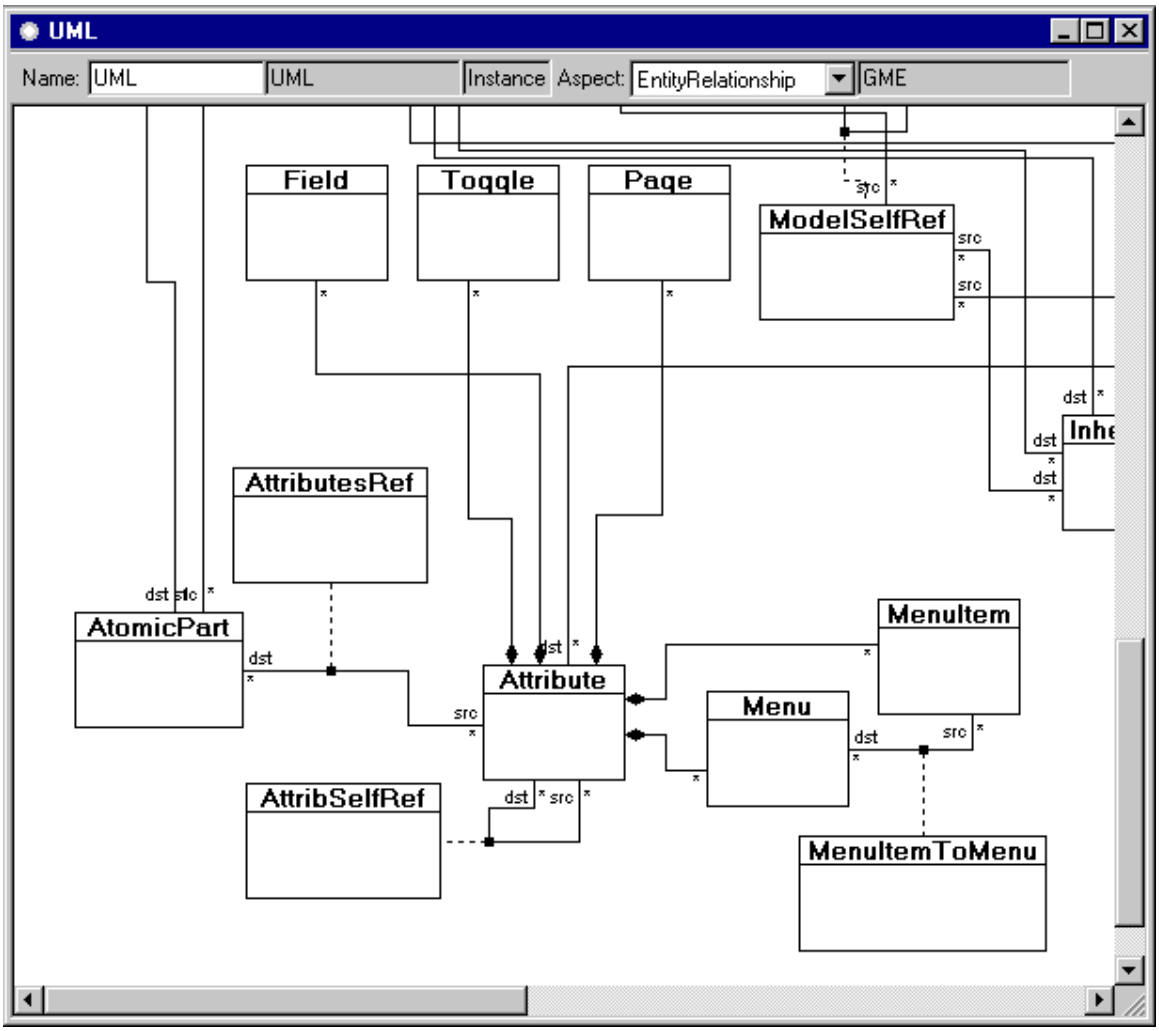


Figure 30: Model and Part Attribute Specification

Paradigm, Category, and Aspect Specification

Resources are allocated within a GME-based DSME according to a named modeling paradigm specification which contains models, atomic parts, and categories. The set of Models used within a given modeling paradigm is partitioned into one or more categories. To properly model these concepts, the UML/GME meta-metamodel includes two objects – the Paradigm and the Category.

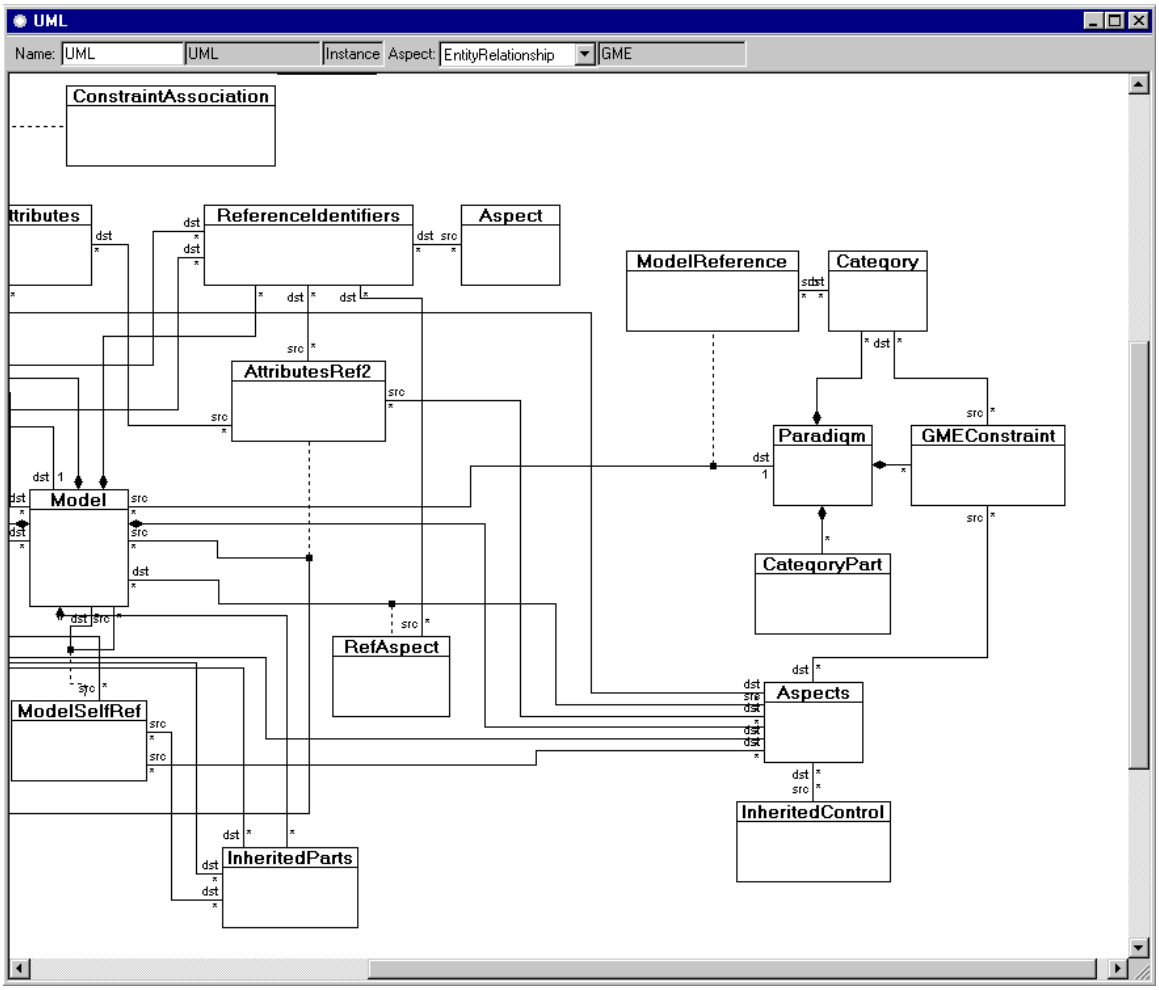


Figure 31: Specifying the Paradigm, Category, and Aspect definitions

Figure 31 shows how the Paradigm object is used to aggregate Category objects, and how the ModelReference association allows Model references to be used to indicate which models "belong" to which Category object. As with earlier examples, the GME referential copy mechanism will be used to indicate which Model models are part of which Category model, so a named association (which will map to a conditionalization relationship) is chosen over direct aggregation.

Notice that the Paradigm object also aggregates GMEConstraint objects. GMEConstraints are identical in structure to the UMLConstraint objects used to specify semantic constraints in metamodels. The difference between these two types of constraints is that GMEConstraints can appear in locations outside the UML portion of a metamodel (for example, to constrain a portion of the *presentation* specification). The meta-metamodel specification shown in Figure 31 allows a GMEConstraint to be placed inside an Aspect specification object. This is necessary since aspects are a presentation mechanism and not part of the "pure" syntactic or semantic behavior specified in the UML portion of a metamodel. Notice that the Aspects class object of Figure 31 has associations with several named association classes. These associations represent the types of modeling objects (parts, connections, etc.) that comprise an aspect. Because the GME metamodeling technique for modeling aspects is to allow the metamodeler to indicate aspect partitioning by collecting several different modeling objects into a single group, in the meta-metamodel, the Aspects class object will be mapped onto a GME representation of conditionalization.

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ELECTRICAL ENGINEERING

METAMODELING – RAPID DESIGN AND EVOLUTION OF DOMAIN-SPECIFIC MODELING ENVIRONMENTS

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Dissertation under the direction of Professor Janos Sztipanovits

Model integrated computing (MIC) is an effective and efficient method for developing, maintaining, and evolving large-scale, domain-specific software applications. Application programs are synthesized from models created using customized, domain-specific model integrated program synthesis (MIPS) environments. The MultiGraph Architecture (MGA), under development at Vanderbilt University's Institute for Software Integrated Systems, is a toolset for creating such MIPS environments.

Until now, these environments have been hand-crafted specifically for each domain. Because common modeling concepts appear in many, if not all, MGA-based MIPS systems, research suggests it is possible to "model the modeling environment" by creating a *metamodel* – a model that describes a particular domain-specific MIPS environment (DSME). By modeling the syntactic, semantic, and presentation requirements of a DSME, the metamodel can be used to synthesize the DSME itself, enabling design environment evolution in the face of changing domain requirements. Because both the domain-specific applications and the DSME are designed to evolve,

efficient and safe large-scale computer-based systems development is possible over the entire lifetime of the system.

This dissertation reviews current metamodeling languages and techniques, examines available DSME resources, develops methods to represent syntactic and semantic modeling language requirements using UML object diagrams and MultiGraph constraint language expressions, and discusses automatic transformation of metamodel specifications into DSMEs. Case studies are used to demonstrate metamodel specification, creation, and translation.

Approved_____ Date_____