Model-Driven Development: A Metamodeling Foundation

Colin Atkinson, *University of Mannheim*

Thomas Kühne, *Darmstadt University of Technology*

Ever since human beings started using computers, researches have been working to raise the abstraction level at which software engineers write programs. The first Fortran compiler was a major milestone in computer science because, for the first time, it let programmers specify *what* the machine should do rather than *how* it should do it. Since then, engineers have continued apace to raise programming abstraction levels. Today's object-oriented languages let programmers tackle problems of a complexity they never dreamed of in the early days of programming.

Model-driven development[1,2] is a natural continuation of this trend. Instead of requiring developers to spell out every detail of a system's implementation using a programming language, it lets them model what functionality is needed and what overall architecture the system should have. Nowadays, compilers automatically handle issues such as object allocation, method lookup, and exception handling, which were programmed manually just a few years ago. By raising abstraction levels still further, MDD aims to automate many of the complex (but routine) programming tasks—such as providing support for system persistence, interoperability, and distribution—which still have to be done manually today.

Although metamodeling is an essential foundation for model-driven development, the traditional "language definition" interpretation of metamodeling doesn't meet all the technical requirements for an MDD infrastructure. However, it can easily be extended to provide the necessary support.

Because of MDD's potential to dramatically change the way we develop applications, companies are already working hard to deliver supporting technology. However, there is no universally accepted definition of precisely what MDD is and what support for it entails. In particular, many requirements for MDD support—where they've been identified—are still implicit. So, after reviewing the underlying motivations for MDD, this article sets out a concrete set of requirements that MDD infrastructures should support. It then analyzes the technical implications of these requirements and offers some basic principles by which they can be supported.

Requirements for model-driven development

The underlying motivation for MDD is to improve productivity—that is, to increase the return a company derives from its software development effort. It delivers this benefit in two basic ways:

- It improves developers' short-term productivity by increasing a primary software artifact's value in terms of how much functionality it delivers.
- It improves developers' long-term productivity by reducing the rate at which a primary software artifact becomes obsolete.

The short-term productivity level depends on how much functionality you can derive from a primary software artifact. The more executable functionality it can generate, the higher the productivity will be. To date, most tool support for MDD centers on this form of productivity; most tool vendors have focused their efforts on automating code production from visual models. However, this addresses only one of the two main aspects of MDD.

The long-term productivity level depends on a primary software artifact's longevity. The longer an artifact stays valuable, the greater its return on investment will be. Thus, a second and strategically more important aspect of MDD is reducing primary artifacts' sensitivity to change. Four main fundamental forms of change are particularly important:

1. *Personnel*. As long as developers store vital development knowledge in their minds, software organizations run the risk of losing such information through personnel fluctuations, which are all too frequent. To ensure that software artifacts outlive their creator's tenure, they must be accessible and useful to as wide a range of people as possible. In addition to being presented concisely, software artifacts should take a form that all interested stakeholders, including customers, can understand easily. Technically this implies that software artifacts must be described using a *concise and tailorable notation*.
2. *Requirements*. Changing requirements have always been a big problem in software engineering, but never more than today. Not only must developers supply new features and capabilities at an ever-increasing rate, but the impact of these changes on the system's existing parts must be low in terms of maintenance efforts and disrupting online systems. They can't simply take enterprise applications offline for extended periods of time to extend the system; they must realize changes while a system is running. At a technical level, this implies the need to support the *dynamic addition of new types at runtime*.
3. *Development platforms*. Primary software artifacts that are tied to one tool are only useful for the lifetime of that tool. But because tools are constantly evolving, it's obviously advantageous to decouple artifacts from their development environments. Thus, another technical requirement is that tools should store artifacts in formats that other tools can use; they should support *high interoperability levels*.
4. *Deployment platforms*. As soon as developers master one new platform technology, another comes along to take its place. To increase primary software artifacts' lifetime, developers must shield them from changes at the platform level. Technically this means that, to the greatest possible extent, they must automate the process of obtaining platform-specific software artifacts from platform-independent ones by applying *user-definable mappings*.

These forms of change can happen concurrently, so the techniques for accommodating them must at least be compatible with one another, and at best complement each other synergistically. However, before we enhance and combine existing techniques for this purpose, let's summarize the technical requirements these techniques should support. An MDD-supporting infrastructure must define

1. The concepts available for creating models and the rules governing their use
2. The notation to use in depicting models
3. How the model's elements represent real-world elements, including software artifacts
4. Concepts to facilitate dynamic user extensions to model concepts, model notation, and the models created from them
5. Concepts to facilitate the interchange of model concepts and notation, and the models created from them
6. Concepts to facilitate user-defined mappings from models to other artifacts, including code

The underlying motivation for MDD is to improve productivity.

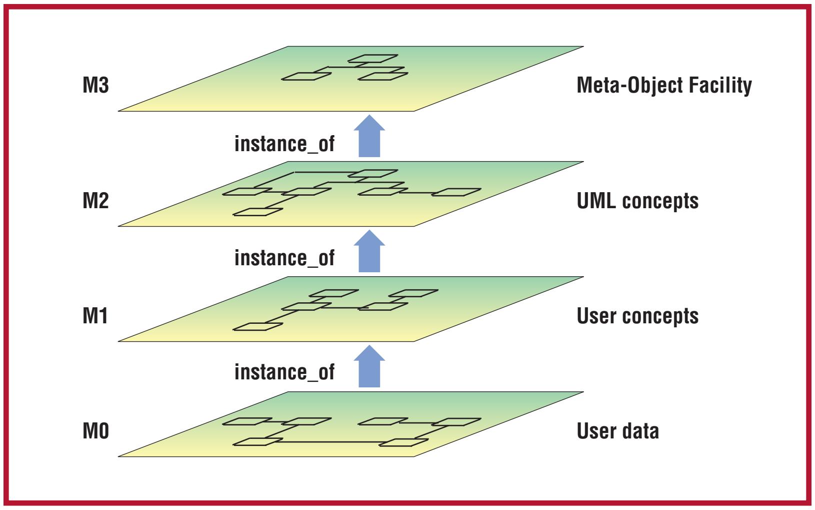


Figure 1. Traditional Object Management Group modeling infrastructure.

Having clarified what capabilities we would like an MDD infrastructure to provide, we can look at how to satisfy these requirements.

Toward an MDD infrastructure

Based on these requirements, it's clear that one of the technological foundations for MDD support is visual modeling. Visual modeling not only directly addresses Requirements 1–3 just described, but also has a long record of success in various engineering disciplines—including software engineering—as a way of effectively using human visual perception.

The technology with the best track record for supporting flexible language extension is object orientation. By letting developers extend the set of available types, object-oriented languages directly support Requirement 4, albeit in a static (that is, offline) way. Object-orientation is therefore generally regarded as one of the other key foundations of MDD.

Finally, the approach that's been most effective at addressing Requirements 5 and 6 defined earlier is the use of metalevel description techniques. These are vital for providing dynamic as well as static support for Requirement 4. With metalevel description techniques of modeling constructs and user types, you can fully customize models to a certain domain, or class of stakeholders, and add new types dynamically at runtime.

The challenge we face in creating an infrastructure for MDD, therefore, is optimally integrating visual modeling, object orientation, and metalevel description techniques. We will first analyze the existing approach for doing this and then suggest some enhancements that better address all six technical requirements listed earlier.

Traditional MDD infrastructure

Figure 1 illustrates the traditional four-layer infrastructure that underpins the first generation of MDD technologies—namely the Unified Modeling Language[3] and the Meta-Object Facility.[4]

This infrastructure consists of a hierarchy of model levels, each (except the top) being characterized as an *instance of* the level above. The bottom level, M0, holds the *user data*—the actual data objects the software is designed to manipulate. The next level, M1, is said to hold a *model* of the M0 user data. User models reside at this level. Level M2 holds a model of the information at M1. Because it's a model of a model, it's often referred to as a metamodel. Finally, level M3 holds a model of the information at M2, and therefore is often called the meta-metamodel. For historical reasons, it's also referred to as the Meta-Object Facility.

This venerable four-layer architecture has the advantage of easily accommodating new modeling standards (for example, the Common Warehouse Metamodel) as MOF instances at the M2 level. MOF-aware tools can thus support the manipulation of new modeling standards and enable information interchange across MOF-compatible modeling standards.

Although it's been a successful foundation for first-generation MDD technologies, this traditional infrastructure doesn't scale up well to handle all technical Requirements 1–6 described earlier. In particular, we can identify four key problems:

- No explanation exists of how entities in the infrastructure relate to the real world. Does the infrastructure accommodate real-world elements or do they lie outside?
- The infrastructure implies that all instance-of relationships between elements are fundamentally of the same kind. Is this a valid approach or should we be more discriminating?
- No explicit principle exists for judging at which level a particular element should reside. Using a single instance-of relationship to define the metalevels always seems to introduce inconsistencies. Can we use instantiation to define metalevel boundaries and, if so, how?
- A preference exists for using metalevel description (sometimes in the form of stereotypes) to provide predefined concepts. How can we integrate the other way of supplying predefined concepts—libraries of (super-) types, to be used or specialized—within the architecture?

Table 1

Language definition

Concept	Purpose	UML solution
Abstract syntax	The concepts from which models are created (see Requirement 1)	Class diagram at level M2
Concrete syntax	Concrete rendering of these concepts (see Requirement 2)	UML notation, informally specified
Well-formedness	Rules for applying the concepts (see Requirement 1)	Constraints on the abstract Syntax (using the Object Constraint Language, for example)
Semantics	Description of a model's meaning (see Requirement 3)	Natural language specification

To address these problems, we must adopt a more sophisticated view of metamodeling's role in MDD and refine the simple one-size-fits-all view of instantiation. Regarding all instance-of relationships as being of essentially the same form and playing the same role doesn't scale up well for Requirements 1–6. Instead, it's helpful to identify two separate orthogonal dimensions of metamodeling, giving rise to two distinct forms of instantiation.[5,6] One dimension is concerned with language definition and hence uses *linguistic instantiation*. The other dimension is concerned with domain definition and thus uses *ontological instantiation*. Both forms occur simultaneously and serve to precisely locate a model element with the language-ontology space.

Linguistic metamodeling

As indicated before, Requirements 1–3 essentially state the need for a language-definition capability (see Table 1). Much of the recent work on enhancing the infrastructure, therefore, has focused on using metamodeling as a language definition tool. With this emphasis, the linguistic instance-of relationship is viewed as dominant and levels M2 and M3 are regarded as language definition layers.

This approach relegates ontological instance-of relationships, which relate user concepts to their domain types, to a secondary role. In other words, whereas linguistic instance-of relationships cross (and form the basis for) linguistic metalevels, ontological instance-of relationships don't cross such levels; they relate entities within a given level. Figure 2 shows this latest interpretation of the four-layer architecture as embraced by the new UML 2.0 and MOF 2.0 standards. Although the latter take a predominantly linguistic view, it's useful to nevertheless let ontological (intralevel) instantiation establish its own kind of ontological (vertical) metalevel boundaries, as the different shades in level M1 in Figure 2 indicate.

As well as making the existence of two orthogonal metadimensions explicit, Figure 2 illustrates the relationship between model elements and corresponding real-world elements. User objects no longer inhabit the M0 level—instead, the real-world elements that they model do. (The lightbulb denotes the mental concept "Collie.") Note that the real Lassie is represented by object `Lassie`; that is, instance-of is no longer used to characterize the real Lassie as an instance of `Collie`. User objects (that is, model representatives of real-world objects) now occupy the M1 level, along with the types they are ontological instances of. (User data is also considered part of the real world even though it's artificial and might even represent other real-world elements.) Every level from M1 on is regarded as a model expressed in the language defined at the level above it.

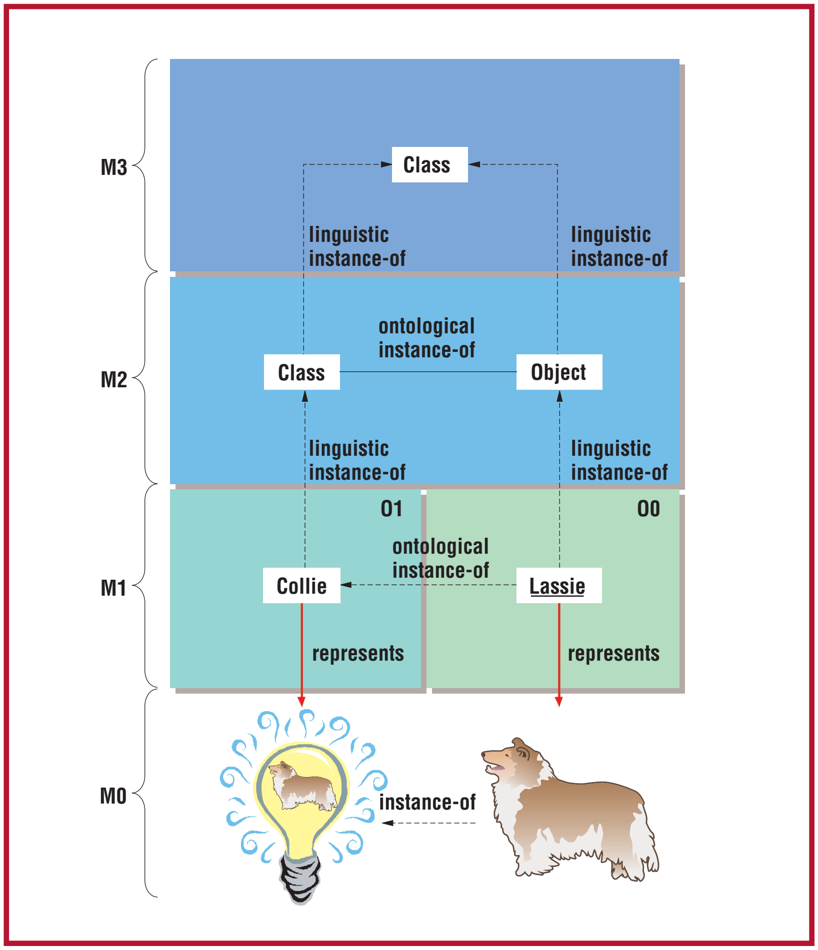


Figure 2. Linguistic metamodeling view.

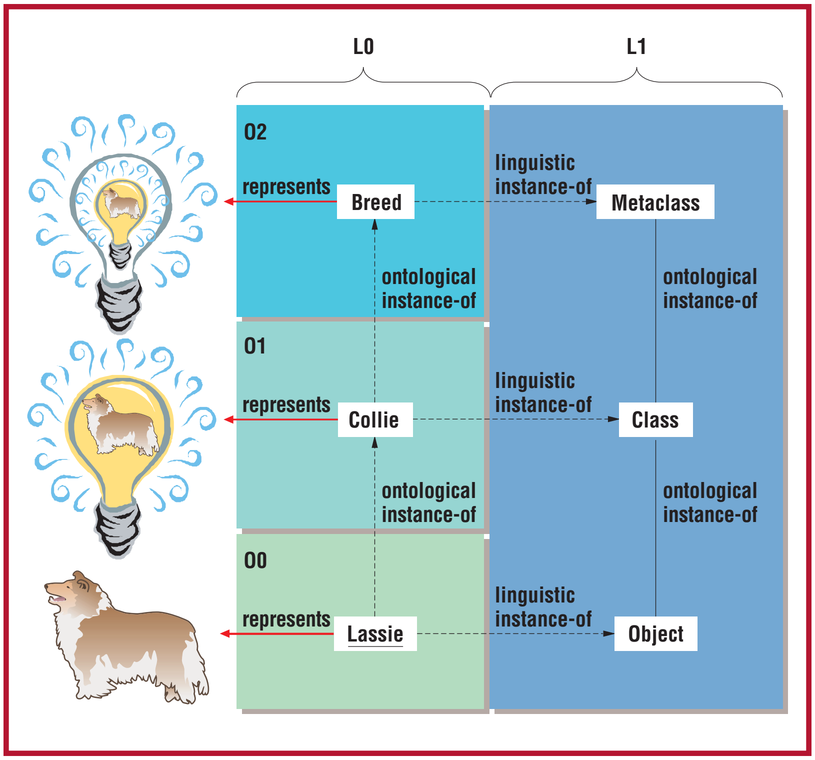


Figure 3. Ontological metamodeling view.

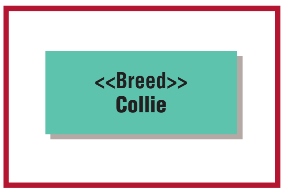


Figure 4. Ontological metamodeling through stereotypes.

Ontological metamodeling

Although linguistic metamodeling addresses many of the technical requirements, it isn't sufficient on its own. In particular, Requirement 4 calls for the capability to dynamically extend the set of domain types available for modeling, and this in turn requires the capability to define domain metatypes, or types of types. We refer to this as *ontological metamodeling* because it's concerned with describing what concepts exist in a certain domain and what properties they have.

Figure 2 contains an example of ontological instantiation. The model element `Lassie` is an ontological instance of `Collie`, and thus resides at a lower ontological level than `Collie`. This expresses the fact that in the real world, the mental concept Collie is the logical type of Lassie.

Figure 2 only contains two ontological model levels, O0 and O1, both contained in linguistic level M1, but we can naturally extend this dimension to give further ontological levels. Figure 3 features another ontological level, O2, showing that we can regard `Collie` as an instance of `Breed`. An ontological metatype not only distinguishes one type from another but also can be used to define metatype properties. For example, `Breed` distinguishes types such as Collie and Poodle from other types (such as CD and DVD) and can also be used to define breed properties, such as where a particular breed originated or what other breed it was developed from.

Figure 3 also makes another important point regarding the relationship of the two metadimensions, linguistic and ontological, because it's a 90-degree clockwise rotation of Figure 2, adding level O2. We have also relabeled levels MO and M1 to LO and L1 to emphasize their linguistic role. Instead of arranging the linguistic metalevels horizontally so as to suggest that the traditional infrastructure's metalevels are linguistic, Figure 3 arranges the ontological metalevels horizontally to suggest that the traditional metalevels are ontological. Both arrangements are equally valid because the traditional infrastructure made no distinction between ontological or linguistic instantiation and no choice about its metalevels' meaning.

Not only are both arrangements—or viewpoints—equally valid, they are equally useful. Just as ontological metamodeling is relegated to a secondary role when we take the linguistic viewpoint, linguistic metamodeling is relegated to a secondary role when we take the ontological viewpoint. Ideally, an MDD infrastructure should give equal importance to both ontological and linguistic metamodeling; neither should be subservient to the other. Unfortunately, this isn't the case in the new UML 2.0 infrastructure.

UML 2.0 and MOF 2.0 emphasize the linguistic dimension. Levels O0 and O1 exist in M1 but aren't explicitly separated by a metalevel boundary. Ontological metamodeling is not excluded per se, but the encouraged mechanisms for enabling it—profiles and stereotypes—have known limitations. While it's possible to express that `Collie` is an instance of `Breed` (see Figure 4), the full arsenal of M1 modeling concepts isn't available for stereotype modeling—for example, a visual model of associations and generalization relationships between metaconcepts.

However, researchers have long recognized the ability to freely model with metaconcepts (that is, fully use an O2 level) as useful. Being able to use metaconcepts such as TreeSpecies[7] or Breed is a big advantage. Figure 5 shows perhaps one of the most mature, established examples of ontological metamodeling: the biological taxonomy for living beings. Metaconcepts such as Breed, Species, and so on serve to let new creature classes be added to the taxonomy. In a software system, they would facilitate the dynamic addition of new types at runtime. Note that you can't cast Breed, Species, and so on as supertypes at the O1 level. While it makes sense to say that Lassie is a Collie, a Dog, and so on, it doesn't make sense to say that Lassie is a Breed, a Species, and so on. Also, it isn't a problem to accommodate level O3 (see Figure 5) in the ontological metadimension, while stereotypes aren't designed to support this.

Ontological metamodeling is particularly important for MDD because it's explicitly called for in two of the main strategies for model transformation defined in the MDA User's Guide.[8] First, it's the basis for the marking mechanism that's envisaged as one of the key ways to support the user-driven definition of model transformation, that is, to support Requirement 6. Second, it's the basis for defining mappings in the framework-based version of type-level transformation. This assumes the existence of an ontologically predefined set of superclasses (with associated predefined mappings) that users specialize with their own application classes.

We've defined a concrete set of requirements that an ideal MDD infrastructure should support. We've also argued that explicitly distinguishing the two orthogonal forms of metamodeling—linguistic and ontological—is the key to fixing some of the problems in the first-generation MDD infrastructure and to scaling it up to satisfy all the identified requirements.

The forthcoming revision of the OMG's MDD infrastructure in the UML 2.0 and MOF 2.0 standards represents a significant step forward in that, for the first time, it accommodates two distinct forms of instantiation. However, two significant problems remain.

First, although the distinction is present, it isn't explicit enough. Although the infrastructure recognizes linguistic metalevel boundaries, ontological boundaries remain implicit. When coupled with the fact that stereotypes remain the preferred mechanism for user metamodeling, it's clear that the new standard is still unduly balanced towards linguistic metamodeling.

Second, in the current profile mechanism, there's still a bias toward locating predefined concepts at the metalevel (that is, as part of the modeling language) rather than as regular user types at the M1 level. This is despite the fact that libraries or frameworks at the M1 level have established a strong track record for making predefined concepts available for direct use or specialization by users. In fact, the MDA User's Guide[8] explicitly exploits this form of reuse and predefinition as a means for defining reusable type mappings.

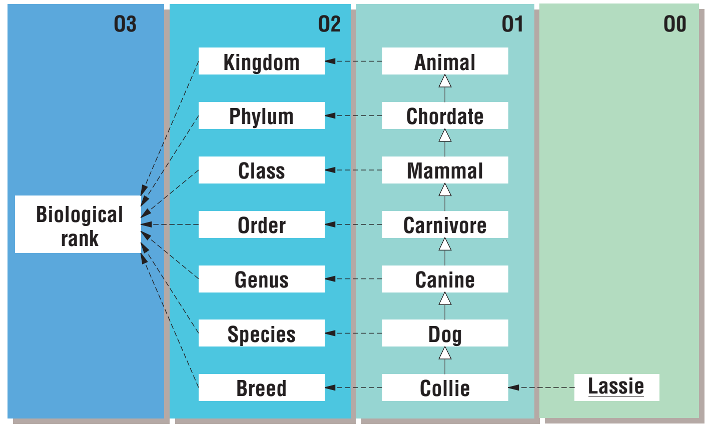


Figure 5. Ontological metamodel of biological classification.

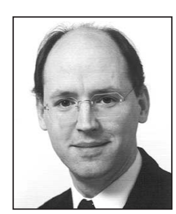
Despite this reservation, the new OMG MDD infrastructure does represent a significant step forward and provides most of the identified technical capabilities. We hope that this article might help improve subsequent versions of the infrastructure in the future.

References

1. J. Mukerji and J. Miller, eds., "Model Driven Architecture," www.omg.org/cgi-bin/doc?ormsc/2001-07-01.
2. D.S. Frankel, *Model Driven Architecture: Applying MDA to Enterprise Computing*, OMG Press, 2003.
3. *OMG Unified Modeling Language Specification*, Object Management Group, 2003, http://doc.omg.org/formal/03-03-01.
4. *Meta Object Facility (MOF) Specification*, Object Management Group, 2003, http://doc.omg.org/formal/02-04-03.
5. C. Atkinson and T. Kühne, "Rearchitecting the UML Infrastructure," *ACM Trans. Modeling and Computer Simulation*, vol. 12, no. 4, Oct. 2002, pp. 290–321.
6. J. Bézivin and R. Lemesle, "Ontology-Based Layered Semantics for Precise OA&D Modeling," *Object-Oriented Technology*, LNCS 1,357, Springer-Verlag, 1998, pp. 151–154.
7. J. Odell, "Power Types," *J. Object-Oriented Programming*, vol. 7, no. 2, Mar./Apr. 1994, pp. 8–12.
8. *XMIVersion 1 Production of XML Schema Specification*, Object Management Group, 2003, http://doc.omg.org/formal/03-05-01.

About the Authors

Colin Atkinson holds the chair of software engineering at the University of Mannheim. His research interests focus on object and component technology and their use in the systematic development of software systems. He received his PhD in computer science from Imperial College London. Contact him at FG Software Engineering, University of Mannheim, L 15, 16, 5. OG, Zi. 520, 68161 Mannheim, Germany; atkinson@informatik.uni-mannheim.de.



Thomas Kühne is an assistant professor at the Darmstadt University of Technology. His research interests focus on object technology, programming language design, component architectures, and metamodeling. He received his PhD from the Darmstadt University of Technology. Contact him at FG Metamodeling, TU Darmstadt, Wilhelminenstr. 7, 64283 Darmstadt, Germany; kuehne@informatik.tu-darmstadt.de.