MDD for Embedded Systems

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About me

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- Independent Consultant
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- Focus on
  - Model-Driven Software Development
  - Software Architecture
  - Middleware

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MDD for Embedded Systems

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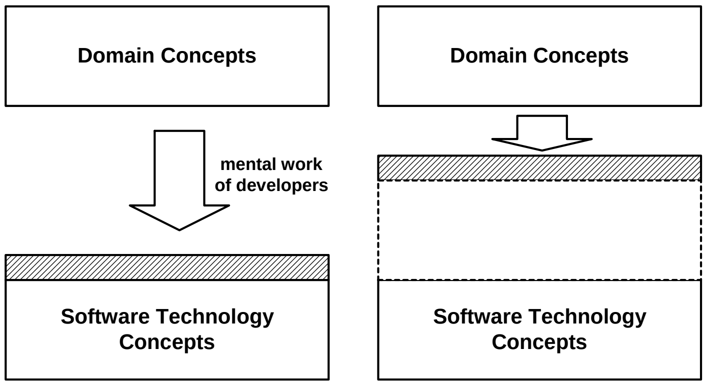
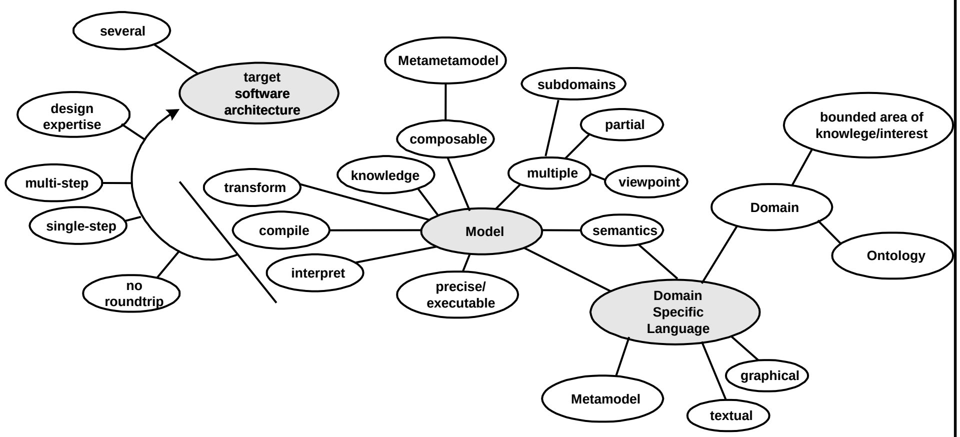
Model-Driven Software Development

- MDSD is about making software development more **domain-related** as opposed to **computing related**. It is also about making software development in a certain domain **more efficient**.

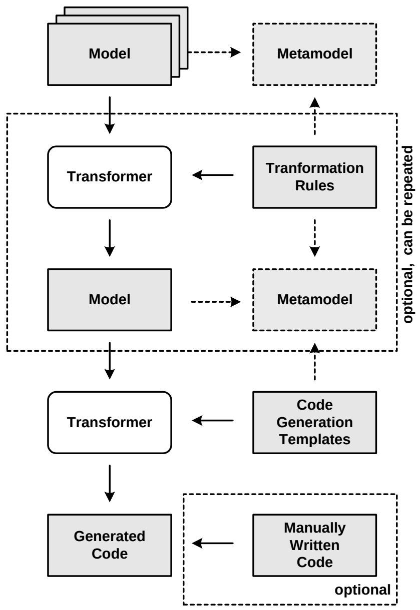


MDSD on a Slide



How does MDSD work?

- Developer develops **model(s)** based on certain metamodel(s).
- Using **code generation templates**, the model is transformed to executable code.
- Optionally, the **generated code is merged** with manually written code.
- One or more **model-to-model transformation steps** may precede code generation.



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What are Embedded Systems

- Well, a very diverse crowd ☺

Characteristics of Embedded Systems

- **Non-homogeneity**, almost every device is different
- **Limited memory**, often only some hundred kB or few MB are available
- **Limited computing power** because the devices often contain only small processors
- **Limited electrical power** because the device might be battery powered
- **Timing requirements** can be more stringent:
  - Soft real time
  - Hard real time
- **Network connection** can either be permanent or intermittent
- **High system complexity**, “configuration hell”
- **Concurrency**, simulated (threads, processes) and real (many nodes in the system)
- **Hardware-Dependent**, integration with various sensors and communication technologies

Challenges

- To develop **resource efficient** systems with as little runtime overhead as possible
- To build **architecturally coherent** systems
- To handle **system complexity** including **QoS aspects**
- To systematically handle the **variabilities** among different products in a product line
- Often they need to run on **different OS / hardware** configurations
- To **integrate the various tools** used in the production process
- Consider the **hardware** ("Systems Engineering")

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Context

- In embedded systems, indirection, frameworks and other **classical means of expressing abstractions** cannot be used for reasons of performance and other determinism.
- With MDSD, **abstractions can still be expressed** at modeling/source time. Using code generation, an efficient **implementation can be generated** that does not suffer from any performance overhead.
- Code generators can include **optimizations** (just as compilers do)
  - to generate the **most efficient implementation** wrt. to certain properties (space, time, ...)
  - **Parts/aspects** of the specific system instance (think product lines) can be **ommitted** from the generated system

What is efficient code?

- For example, in C you can do the following:
  - Deliberately making things **inline**
  - Using **function pointers** (maybe hidden behind macros) to access configurable functionality
  - Decision tables based on **arrays indexing into each other** (e.g. for state machines)
  - Generating code to **directly call** a (potentially remote) entity, thereby “removing the middleware” completely
  - Based on application features, generate the **smallest possible OS configuration**
- Manually coding some of these things is very **tedious and error prone**
  - This is why things are **brittle** when used in manual coding
  - But a **generator** can use these techniques **consistently and reliably**

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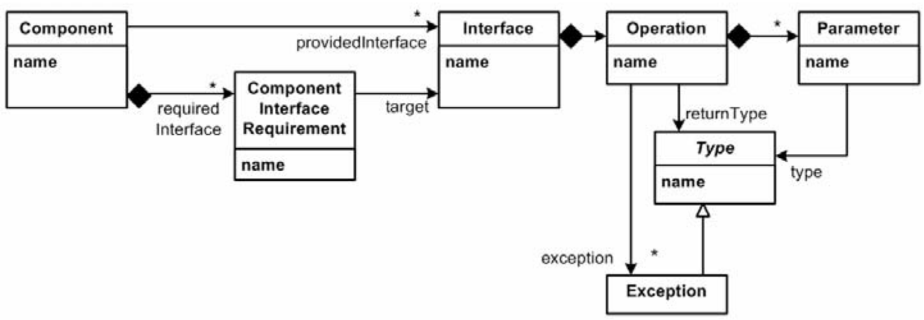
Context

- Many embedded systems are actually large, distributed networked systems where **each part must play along** certain rules to make the overall system work.
  - Often, many different organizations/vendors cooperate to engineer the overall system (e.g. automotive systems)
- A common architecture must be **established and enforced** to make the system deliver on its (functional and non-functional) requirements
- MDSD can help by
  - **Formally defining architectures** via architectural meta models
  - **Checking constraints** on actual applications models (static, as well as dynamic)
  - **Generating implementation skeletons** for developers to add their application logic in an architecturally conforming way

Example: A CBD Meta Model (Type Viewpoint)

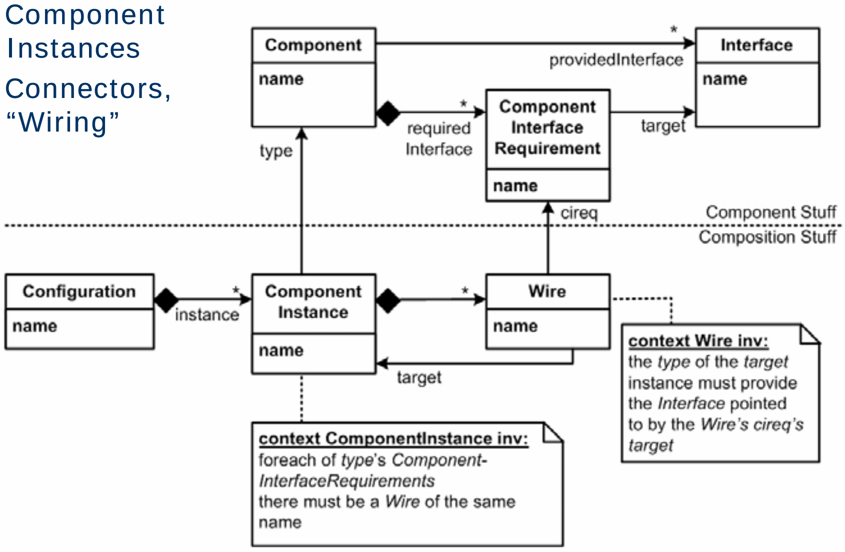
- Components
- Interfaces
- Operations



MDD for Embedded Systems

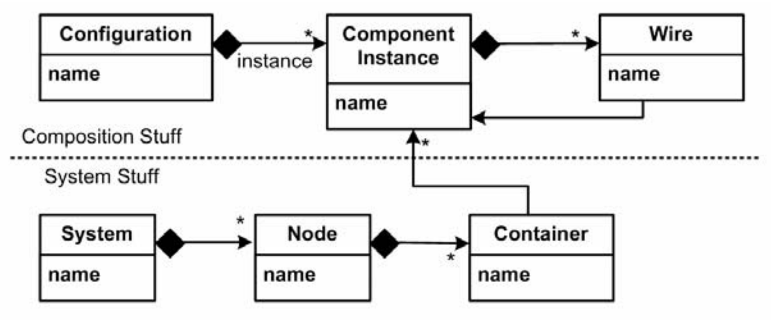
Example: A CBD Meta Model (Composition Viewpoint)

- Component Instances
- Connectors, “Wiring”



Example: A CBD Meta Model (System Viewpoint)

- Hardware (Processors, Networks, Busses)
- Deployment & Configuration



Example: A CBD Meta Model (Constraints)

- A wire's target's type must provide the interface to which the wire's interface requirements points:

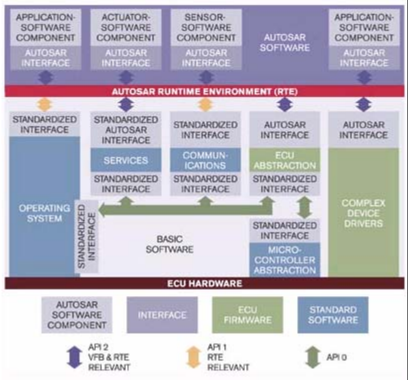
```
context Wire ERROR “wrong type at the other end”:
       target.type.providedPorts.interface.exists(
              i | i == cireq.target );
```

- The required interface objects of a component need to have unique names (that's an assumption required by the code generator)

```
context Component ERROR “ports must have unique names”:
       requiredInterface.forAll( r1 |
         !requiredInterface.exists( r2 |
            r1 != r2 && r1.name == r2.name ) );
```

Example: AUTOSAR

- AUTOSAR is a **standard software architecture for automotive ECUs**
  - although large portions could be used outside automotive systems, too.
- It adresses many aspects of automotive software, the most important aspects in my opinion are
  - Formal **definition** of what a **component** is
  - A **deployment, configuration and communications infrastructure** for component instances
  - A **modeling language** (based on a formal meta model) for describing AUTOSAR systems



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Context

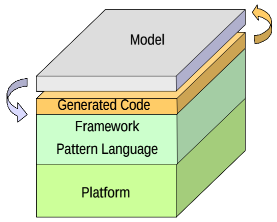
- Distributed Realtime-Embedded (DRE) systems are among the **most complex systems on the planet:** large, distributed, QoS-aware, reliable.
- These systems consist of so many parts that **describing, managing and orchestrating** them requires sophisticated abstractions and formalisms.
- The systems built from these parts need to **address certain QoS properties** (i.e. global constraints) wrt. to timing, resource consumption, liveliness, etc.
- MDSD can help by
  - **Formally describing the parts** that make up the system including their **metadata** necessary for QoS
  - From the models, **simulations** can be derived that check whether certain dynamic properties hold
  - **Various algorithms** (constraint solvers, etc.) can help in coming up with (more or less) ideal system configurations for meeting the global constraints.

The Role of Patterns

- Patterns are **essential** in documenting best practices (“proven solutions for recurring problems”).
- Patterns **document** considerations, context, tradeoffs and a solution – they are meant for humans, not tools!
- There are relationships to MDD, however:
  - Patterns can be **“implemented” by the generator** (after the architect has manually decided to use them!)
  - Patterns & Pattern Languages can help you come up with **an architecture** and an **architectural meta model**
    - for a system (Remoting Infrastructures)
    - or a given aspect of a system (Pipes & Filters)
- Always be **sceptical** if you read “this tool supports patterns – all the existing 23”

The Role of Frameworks & Middleware

- **Middleware encapsulates** quite a bit of the accidental system complexity.
- **Example Middleware platforms** include
  - Various RTOSs such as Osek, QNX, VxWorks
  - CORBA, RT-CORBA, (Lw-)CCM
  - Data Distribution Service (DDS)
- However, even with this level of abstraction, the **remaining complexities are still challenging** enough to make manual work unrealistic.
  - This is especially true for **non-local configuration** where many parameters must be set to compatible values.
- Models and generated code can help work efficiently with powerful and complex platforms, middlewares and frameworks



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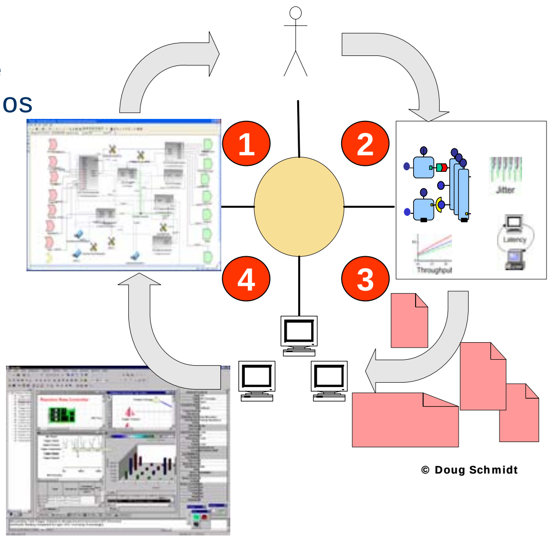
Simulation (Systems Execution Modeling)

- Compose **scenarios**
- Associate **performance properties** with scenarios
- **Configure workload generators** to run experiments
- **Feedback results** into models to verify if deployment plan & configurations meet performance requirements



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Non-Local Optimizations

- Once systems get really big, it becomes **infeasible to manually structure** the system according to a set of given constraints.
  - Consider the problem of deploying hundreds of components to a limited set of computing resources so that the overall system **latency is minimized** and **reliability is optimized.**
- You can use **automatic optimization** techniques such as
  - Constraint Solvers based on Predicate Logic (Prolog)
  - Genetic Algorithms
- You can do this with models because the **system structure is formally described**; the optimizers can work on these models.
  - You might want to use simulation to verify some of the solutions

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Context

- Embedded systems are often **part of a product line** where products exhibit a **well-defined set of variabilities** among each other, as well as many commonalities.
- These variabilities must be **formally expressed** and need to be **efficiently implemented**.
- **Modeling** can be used to express the variabilities
  - Feature modeling for non-structural variability
  - Custom DSLs for structural variability
- **Code Generation** is a way to implement these variabilities
  - Since no runtime overhead is incurred, this is one of the preferred ways of implementing variabilities in embedded systems

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- What is MDSD
- What are Embedded Systems
- The Challenges and MDD
  - Resource Efficiency
  - Architectural Consistency
  - System Complexity
  - Product Lines & Variabilities
  - **Platform Independence / Portability**
  - Tool Integration
  - Hardware & Systems Engineering
- Other Relevant Topics
  - Model-to-Model Transformations
  - Variability Management and Configuration
  - Standards
- Summary

Context

- Since embedded systems are not just software, it is often necessary to **run the same functionality on different infrastructures**:
  - Chips/Architectures
  - Bus Systems
  - Operating Systems
  - OS Configurations: Blocking/Non-Blocking, Scheduler y/n...
  - Threading Libraries
  - Middleware
- ... while the code is (almost) always C ...
- Using #ifdef etc. **does not really scale** well to large systems and many variabilities...

MDD Solution

- You can program your application logic against a **technology-independent API** and then generate the “mapping” to the respective hardware.
- In the generated mapping code, you can use all the “tricks” for efficient generated code explained earlier.
- This is a special case of **Product Lines** that is especially typical – which is why people often don’t consider it PLE.

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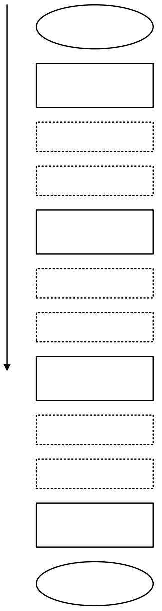
Context

- **Application functionality** has a long history of being modeled with various formalisms – state machines, data flow, mathematical models
  - With the various tools: Matlab/Simulink, Statemate, ...
- More recently, **architectural abstractions** (component models, deployment, etc.) are more and more designed using models.
- One challenge is to **integrate** these different formalisms.
- An example of such an integration is
  - architectural component modeling with UML
  - application logic description with Matlab/Simulink

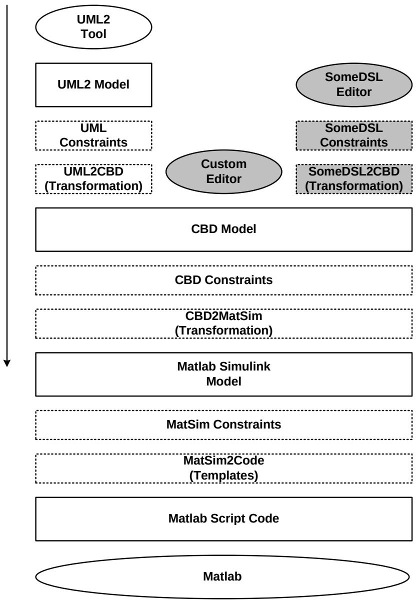
Solution

- Goal: Transform from a profiled UML2 model into a Matlab/Simulink file
- Transform **UML2** to a custom **CBD** model
- Transform **CBD** model into **Matlab/Simulink** model
- **Generate .m file** that can be imported into Matlab/Simulink to build the actual model
- Various **model validation** steps in between
- A **layouting engine** is also integrated (not shown)

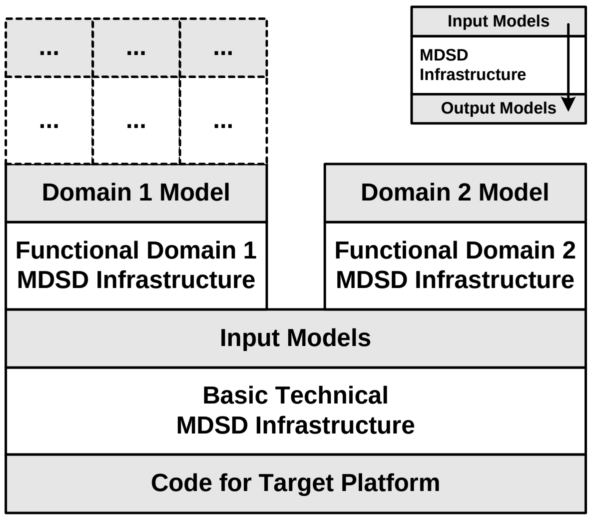


Solution II: Why the separate intermediate models?

- Expressive **validations** can be done at each level
- **You don't have to deal** with the **intricacies** of the UML2 meta model very often – only in the first step!
- You can easily **integrate custom editors** instead of a UML tool
- It is easy to **cascade additional DSL layers** (typically more domain specific) on top of the CBD model



Solution III: Cascading DSLs



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Hardware (Systems Engineering)

- Most embedded systems are not only software – they are a part of a system, i.e. **hardware is also a part** of the game.
  - This is where systems modeling/systems engineering comes in
- Models can represent any concept, not just software, i.e. **a system model can also contain hardware models**
  - hosts, sensors, actuators, networks,
  - each of them described with relevant characteristics such as bandwidth, power, etc.
  - See also: SysML
- You can easily have **software and hardware** (and their relationships) **in the same model**.
  - Optimizations can consider both, if you can describe the hardware characteristics well enough.

„Generating Hardware“

- In contrast to general opinion, **it is possible to generate hardware.**
- Well, sort of.
- The way this works is to:
  - Describe the system to be built using models
  - Generate an “implementation” in e.g. Structured Text
  - “Burn” an FPGA from this specification (FPGA = Field Programmable Gate Array)
- This is a **special case of platform independence** – in this case the platform is an FPGA device.

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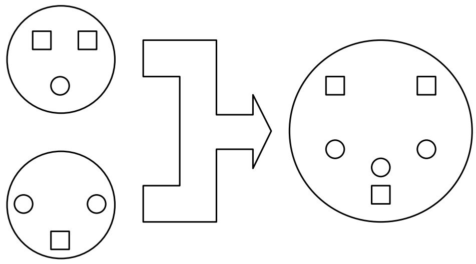
Why M2M

- **M2M transformations are important** to
  - Modularize models
  - Separate concerns in models
  - Keep models on various abstraction levels synchronized
  - Transform models between different tools
- Several different approaches are available: textual/graphical, declarative/procedural/functional
- Tools are becoming **mature**, there are **several** available today:
  - ATL
  - Extend
  - QVT Operations

Model Merging

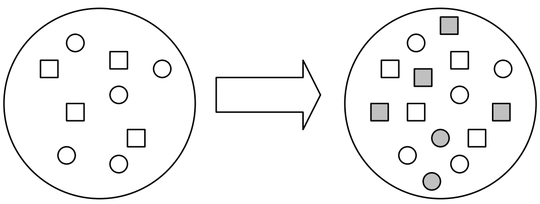
- Several models are **merged** with each other.



- Implications of model merging
  - Typically **easy to implement** (no actual transformation)
  - Meta models are obviously the same
  - Useful if models need to be **modularized** (team issues, performance, ...) and then put together for a complete build

Model Modifications

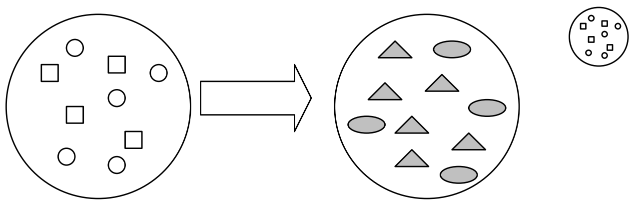
- An existing Model is **modified "in place".**



- Implications of model modification
  - An existing model is **enhanced at generation time**, adding elements (e.g. the index page of a web page)
  - The model is based on the same metamodel before and after the modification
  - little initial implementation overhead (e.g. using Java code)
  - tricky for bigger changes

Model Transformations

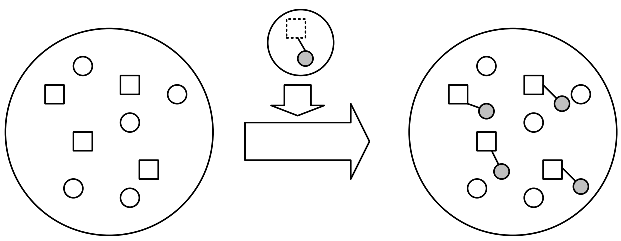
- A model is **transformed into another model**; the input model is left unchanged.



- Implications of model transformations
  - clean separation: **separate models, separate metamodels**
  - different domains can evolve independently
  - prerequisite for reusing “cartridges“
  - identical copy operations must be programmed explicitly
  - runtime and memory overhead

Model Weaving

- Two (or more) models are **woven with each other** in a non trivial way (unlike merging)

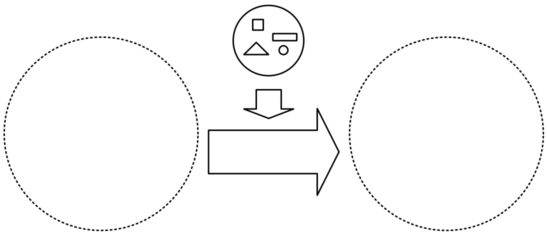


- Implications of model weaving
  - A **weaving model (pointcut) needs to be provided** – which is essentially a special kind of transformation rule
  - **Homogeneous** (shown above) and **Heterogeneous** Aspects can be woven
  - Most of today’s M2M languages don’t address this use case specifically – weavings must be programmed “imperatively” with the transformation language.

Model M

Mixin Models

- The modification or transformation needs to be **parametrized**.



- Implications of mixin models
  - Aka Markup Models
  - Provide **additional (mark up) information** about how a given model should be processed in a modification of transformation
  - Obviously used **together with the other forms**

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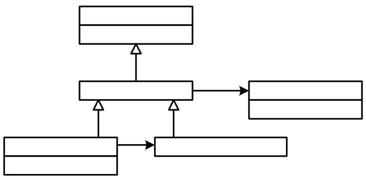
Variability Analysis

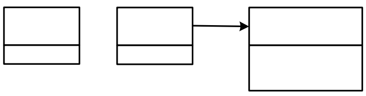
- **Variability analysis** discovers the variable and fixed parts of a product in a domain.
  Parts can be
  - Structural or behavioral
  - Functional or non-functional (technical)
  - Modularized or aspectual
- To define variable parts, we need to **have a commonality base:** a base platform, a common architecture
- There are **two kinds of variability:**
  - positive variability: adds something (optional)
  - negative variability: removes something (essential)
- Another classification: **structural** vs. **non-structural** var.

Structural vs. Non-Structural Variability

- **Structural Variations**
  Example Metamodel



- Based on this sample metamodel,
  you can build a **wide variety of models:**

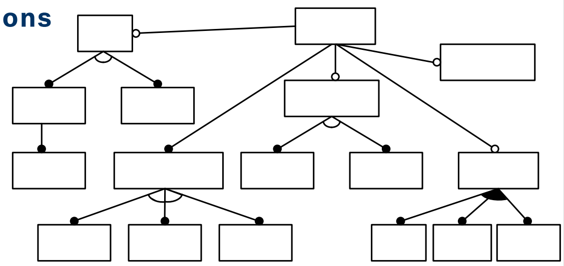


- **Non-Structural Variations**
  Example Feature Models

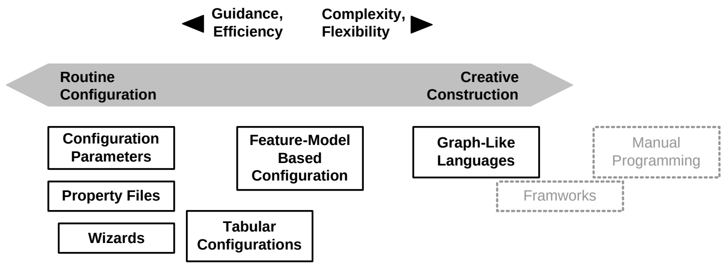
  Dynamic Size, ElementType: int, Counter, Threadsafe

  Static Size (20), ElementType: String

  Dynamic Size, Speed-Optimized, Bounds Check



Rountine Configuration vs. Creative Contruction



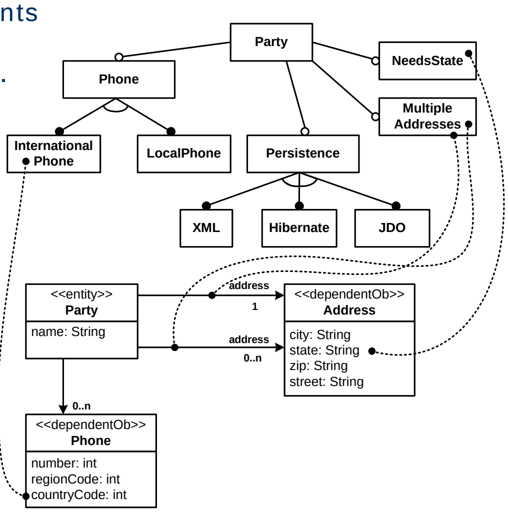
- This slide (adopted from K. Czarnecki) is **important for the selection of DSLs** in the context of MDSD **in general**:
  - The more you can move your DSL „form" to the configuration side, the simpler it typically gets.
  - We will see why this is especially important for behavior modelling.

Variants and Models II

- It is especially useful to **combine structural and non-structural** variations
  – specifically, you may want to „configure" structural models with the help of feature models,
  – we want to describe variants of structural models (and use these variants as generator input)
- Examples:
  - A party may have one or more addresses
  - A party may store telecontacts or not
  - In case of telephone numbers, you may want to store the country code
  - Addresses may have the *state* field (USA)

Variants and Models III

- You can **assign** model elements of the structural model to features in the feature model.
  - The respective model elements are only there if the associated feature is selected,
  - and it's removed if the feature is not there.



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  - **Standards**
- Summary

(Where) Are standards important?

- **Potential examples** for standardization include Meta meta models, meta models, modeling languages (i.e. MM + Syntax), profiles, tools
- Standards are often **very broad and unspecific to a given domain** (UML, SysML)
  - This might improve interop and tool availability,
  - But also incurs a lot of accidental complexity
- Concrete Advice wrt. **UML**:
  - You might want to use UML for modeling (although specific DSLs are usually better),
  - but you **should not use the UML meta model** for (invisible) intermediate meta models.
  - **Always define your own meta model** independent of UML and then (maybe) map it to a profile!

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Summary

- The Embedded community is **adopting MDD very quickly** (and in some areas it has been done for a long time anyway)
- Many of the advantages of MDD can be **exploited especially well** in embedded systems
- **Tooling is mature and usable**... the Eclipse Modeling Project, openArchitectureWare and modern UML tools provide a good starting point.

Some advertisement ☺

- For those, who speak (or rather, read) german:

  Völter, Stahl:

  Modellgetriebene Softwareentwicklung
  Technik, Engineering, Management

  dPunkt, 2005

  www.mdsd-buch.de

Update currently in progress, with Arno Haase and Sven Efftinge as additional coauthors

- A **very much updated** translation is under way:
  Model-Driven Software Development,
  Wiley, Q2 2006

  www.mdsd-book.org