Meeting the Challenges of Ultra-Large-Scale Systems via Model-Driven Engineering

February 2, 2007

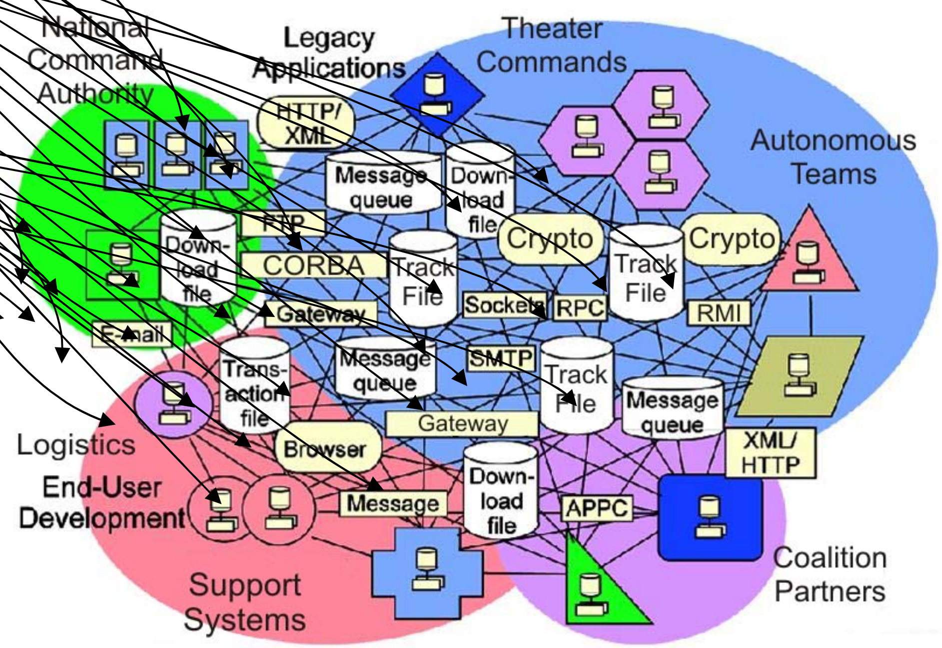
Dr. Douglas C. Schmidt
d.schmidt@vanderbilt.edu
www.dre.vanderbilt.edu/~schmidt

Institute for Software Integrated Systems
Vanderbilt University
Nashville, Tennessee

New Demands on Distributed Real-time & Embedded (DRE) Systems

Key challenges in the ***problem space***

- Network-centric, dynamic, very large-scale "systems of systems"
- Stringent simultaneous quality of service (QoS) demands
- Highly diverse, complex, & increasingly integrated/autonomous application domains

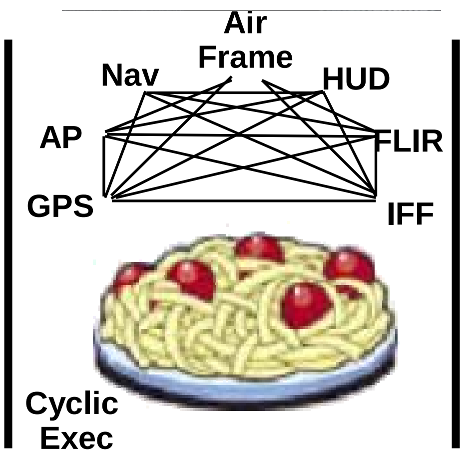


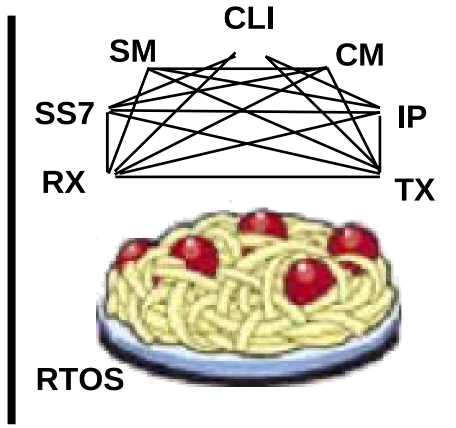
Key challenges in the ***solution space***

- Vast accidental & inherent complexities
- Continuous evolution & change
- Highly heterogeneous (& legacy constrained) platform, language, & tool environments

Mapping & integrating *problem artifacts* & *solution artifacts* is hard

Evolution of DRE Systems Development





Technology Problems

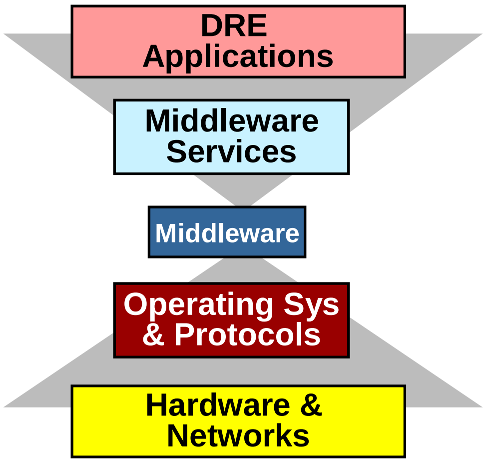
- Legacy DRE systems often tend to be:
  - Stovepiped
  - Proprietary
  - Brittle & non-adaptive
  - Expensive
  - Vulnerable

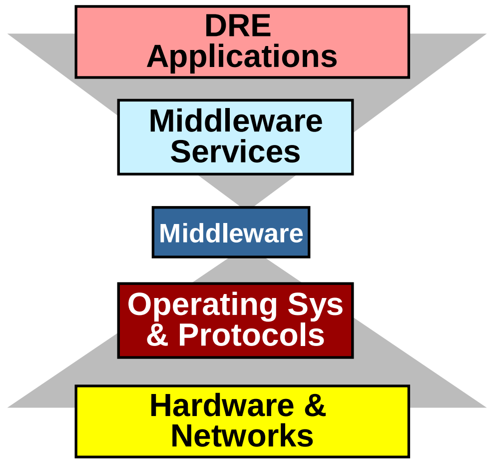
Mission-critical DRE systems have historically been built directly atop hardware

- Tedious
- Error-prone
- Costly over lifecycles

Consequence: Small changes to legacy software often have big (negative) impact on DRE system QoS & maintenance

Evolution of DRE Systems Development





Technology Problems

- Legacy DRE systems often tend to be:
  - Stovepiped
  - Proprietary
  - Brittle & non-adaptive
  - Expensive
  - Vulnerable

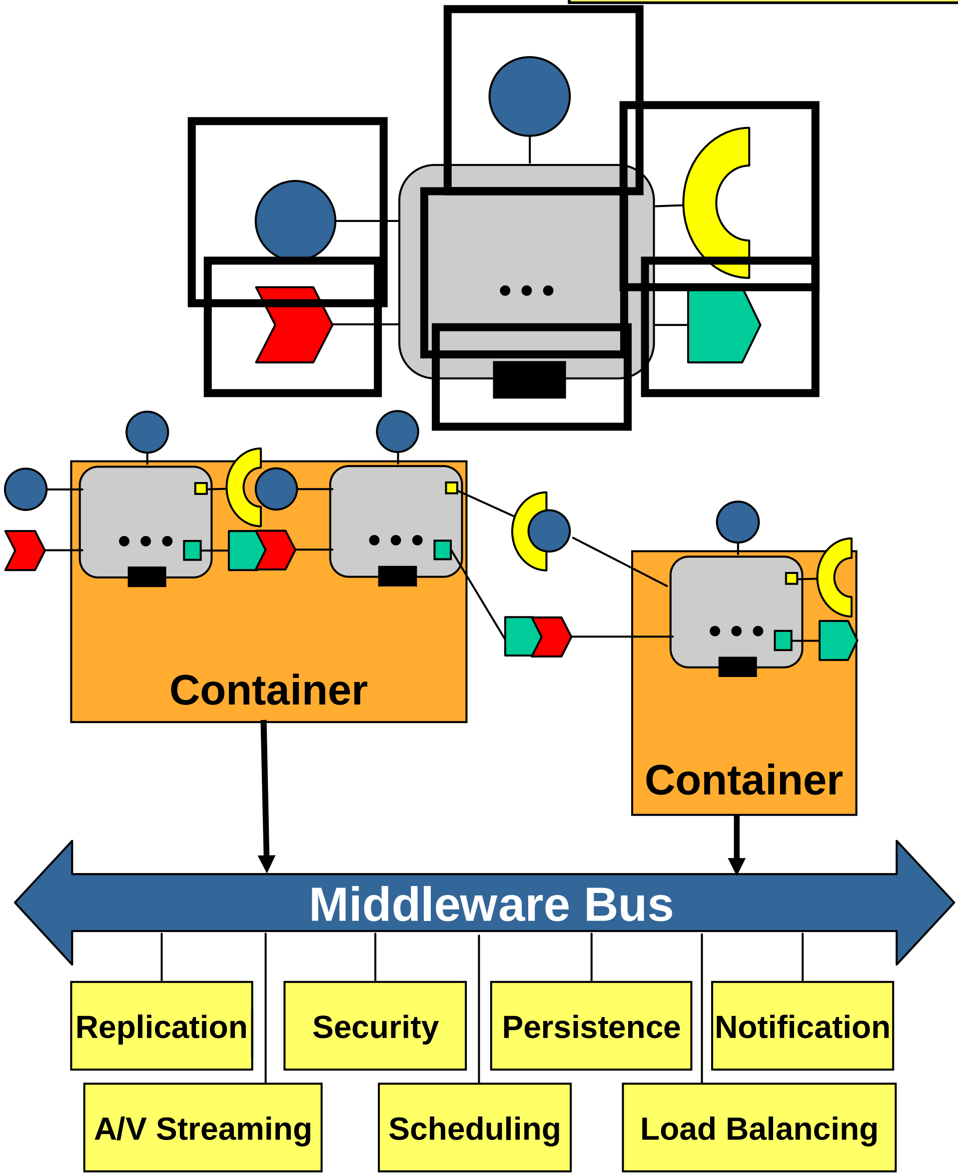
Mission-critical DRE systems historically have been built directly atop hardware

- Tedious
- Error-prone
- Costly over lifecycles

- Middleware has effectively factored out many reusable services from traditional DRE application responsibility
  - Essential for ***product-line architectures***
- Middleware is no longer the primary DRE system performance bottleneck

Overview of Component Middleware

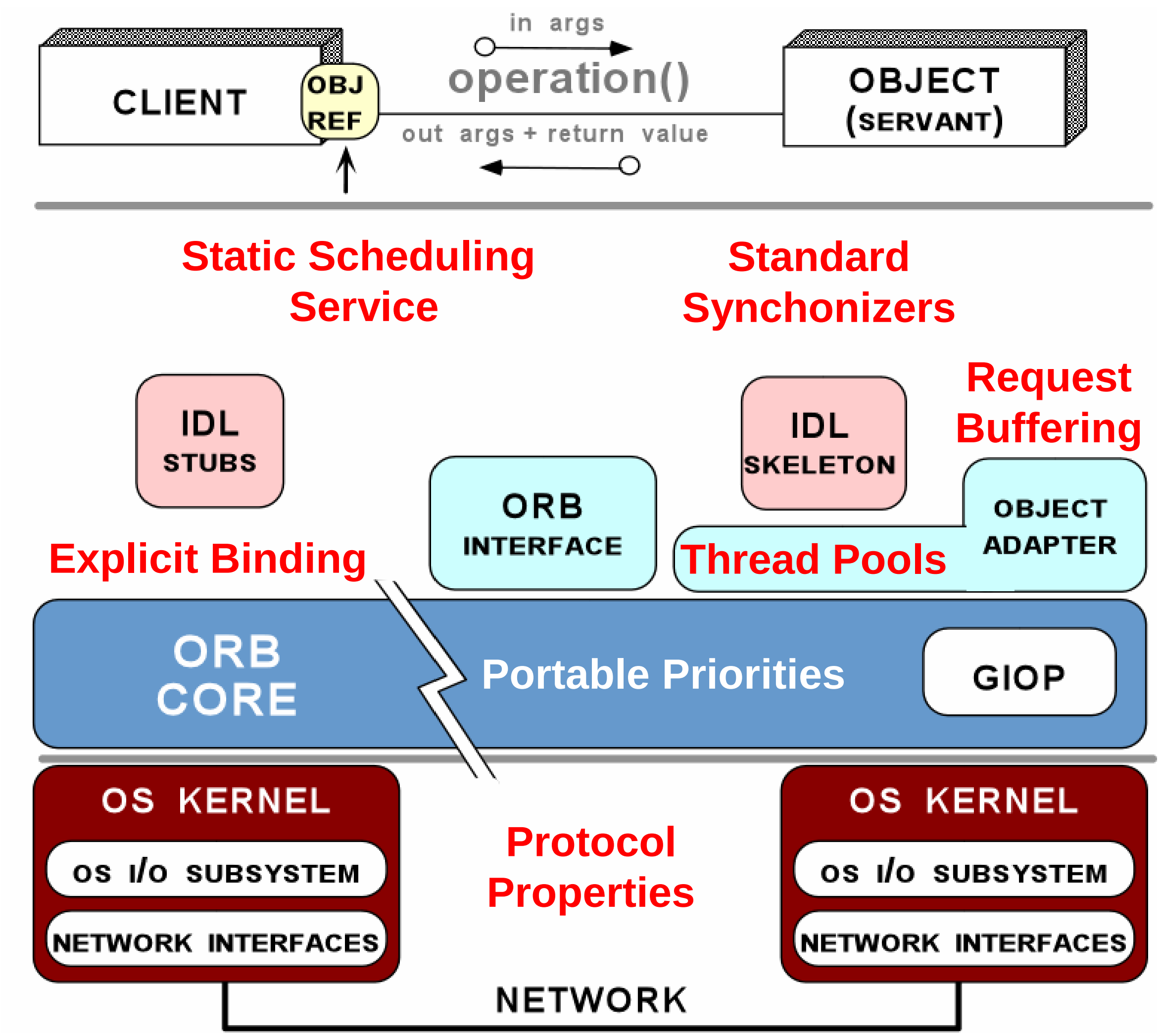
"Write Code That Reuses Code"



- *Components* encapsulate application "business" logic
- Components interact via *ports*
  - *Provided interfaces*, e.g.,facets
  - *Required connection points*, e.g., receptacles
  - *Event sinks & sources*
  - *Attributes*
- *Containers* provide portable execution environment for components that have common operating requirements
- Components/containers can also
  - Communicate via a *middleware bus* and
  - Reuse *common middleware services*

DOC Middleware for DRE Systems (1/2)

Client Propagation & Server Declared Priority Models

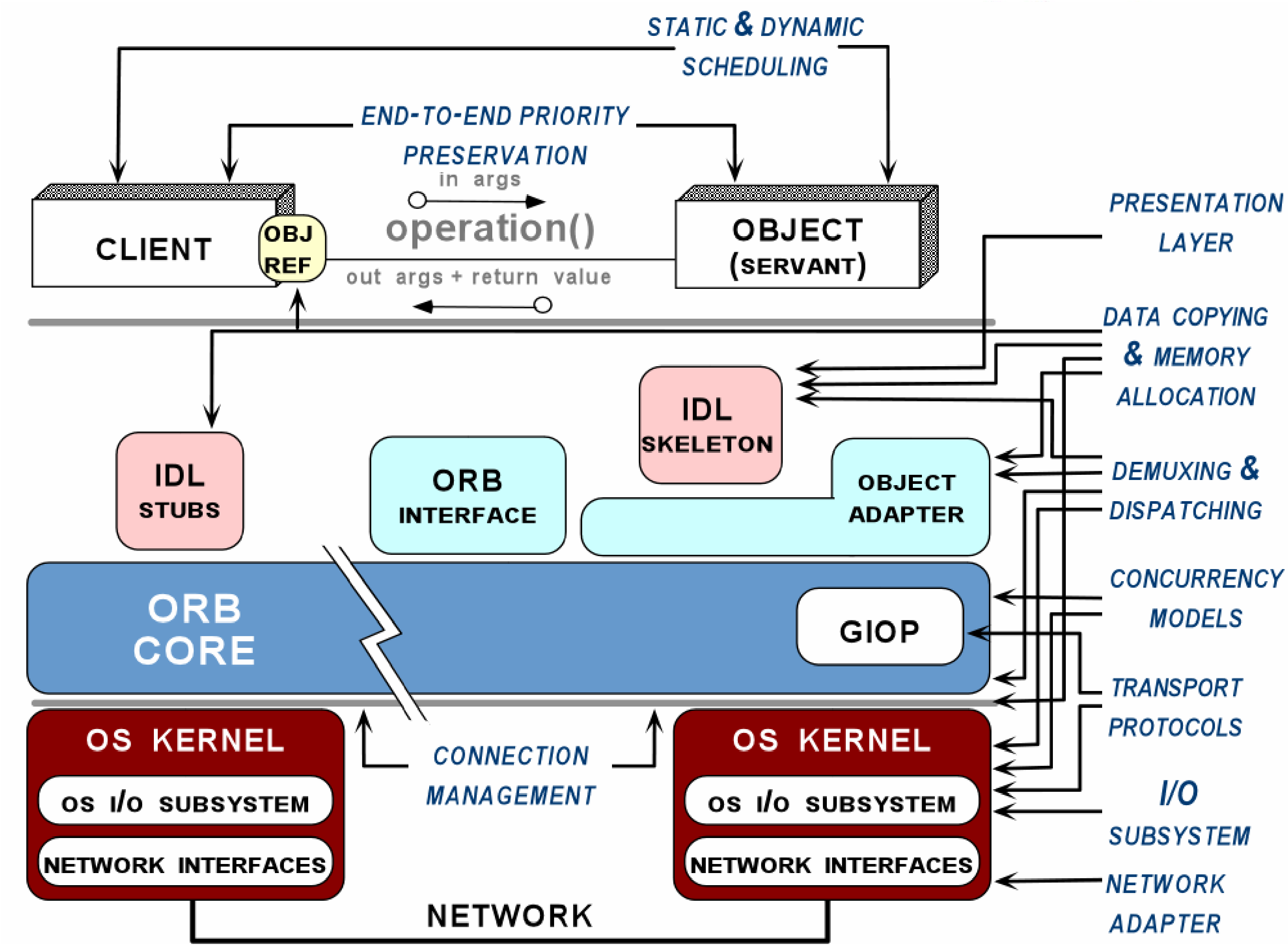


- ***CORBA*** is standard middleware
- ***Real-time CORBA*** adds QoS to classic CORBA to control:

  1. ***Processor Resources***
     - Thread pools
     - Priority models
     - Portable priorities
     - Standard synchronizers
     - Static scheduling service
  2. ***Network Resources***
     - Protocol policies
     - Explicit binding
  3. ***Memory Resources***
     - Request buffering

- These capabilities address key DRE application development & QoS-enforcement challenges

DOC Middleware for DRE Systems (2/2)



TAO is an open-source version of Real-time CORBA

- >> 1,000,000 SLOC
- 100+ person years of effort

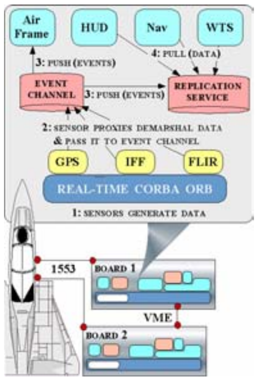
Pioneered R&D on DRE middleware design & optimizations

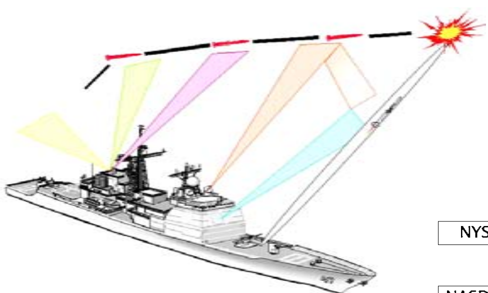
TAO is basis for *many* middleware R&D efforts

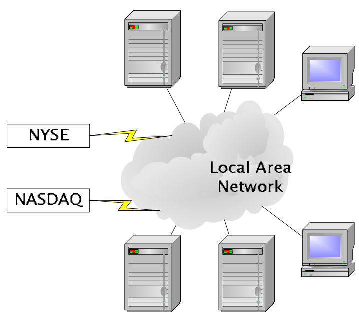
Example of good synergy between researchers & practitioners

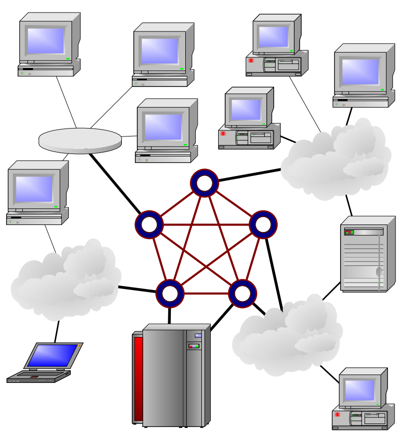
www.dre.vanderbilt.edu/TAO/

Applying TAO in Mission-Critical DRE Systems

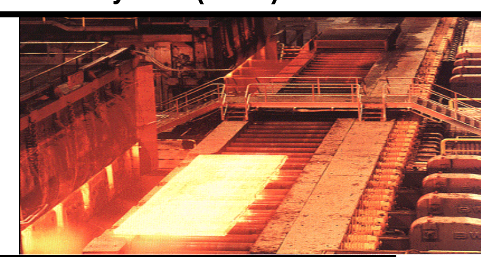








Organization	Application Domain
Boeing	Aircraft mission & flight control computers
SAIC	Distributed interactive simulation (HLA/RTI)
ATDesk	Automated stock trading
Raytheon	Aircraft carrier & destroyer computing systems
Cisco & Qualcomm	Wireless/wireline network management
Raytheon & Army	Joint Tactical Terminal (JTT)
Contact Systems	Surface mounted “pick-and-place” systems
Turkish Navy	Shipboard resource management
Krones	Process automation & quality control
Siemens	Hot rolling mill control systems
LMCO & Raytheon	Dynamic shipboard resource management (DDG)
CUSeeMe	Monitor H.323 Servers
Northrup-Grumman	Airborne early warning & control (AWACS)
JPL/NASA	SOFIA telescope, Cassini space probe
BAE Systems	Joint Tactical Radio System (JTRS)



www.dre.vanderbilt.edu/users.html

Component Middleware for DRE Systems

Event Notifications

Dynamic & Static Scheduling

Multimedia Streaming

Security

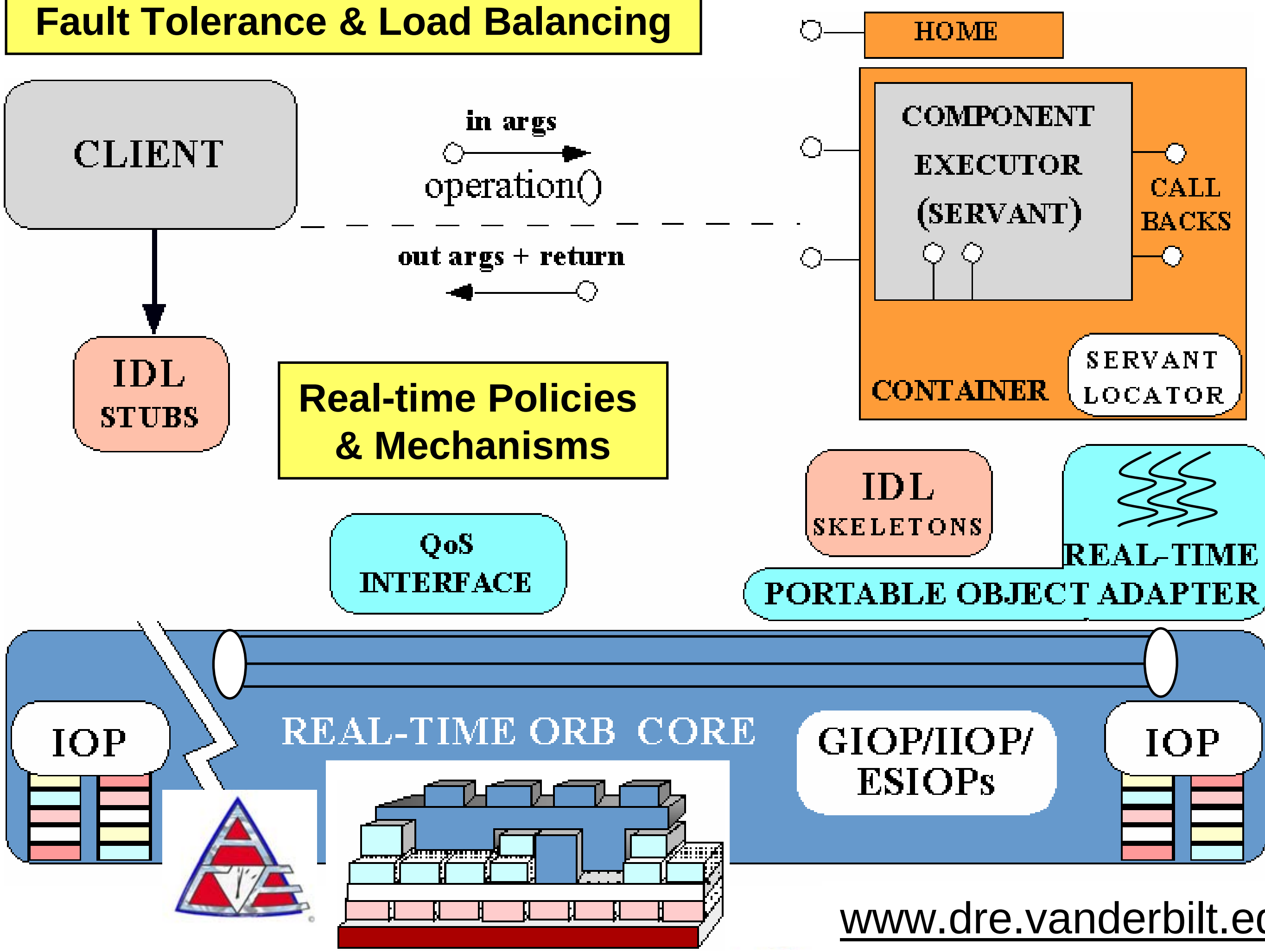
Component Implementation Definition Language

Fault Tolerance & Load Balancing

Component Deployment & Configuration

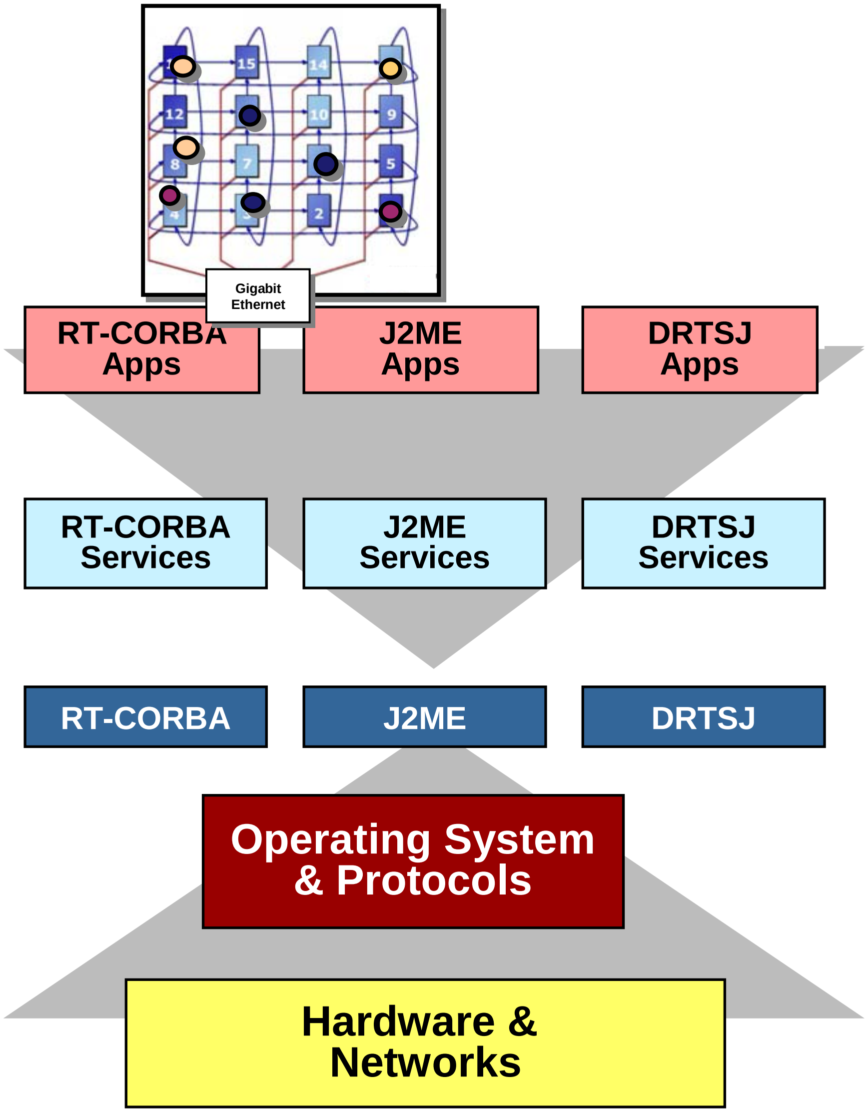
Real-time Policies & Mechanisms

Time/space Optimizations

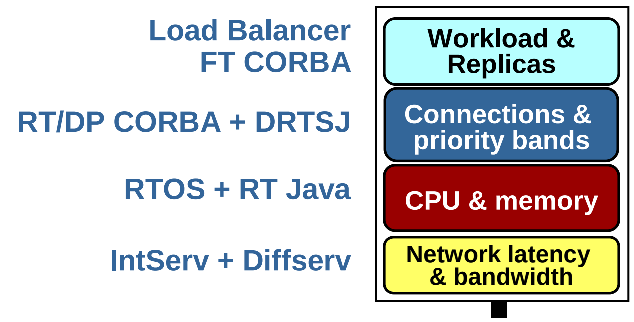


www.dre.vanderbilt.edu/

DRE Systems: The Challenges Ahead



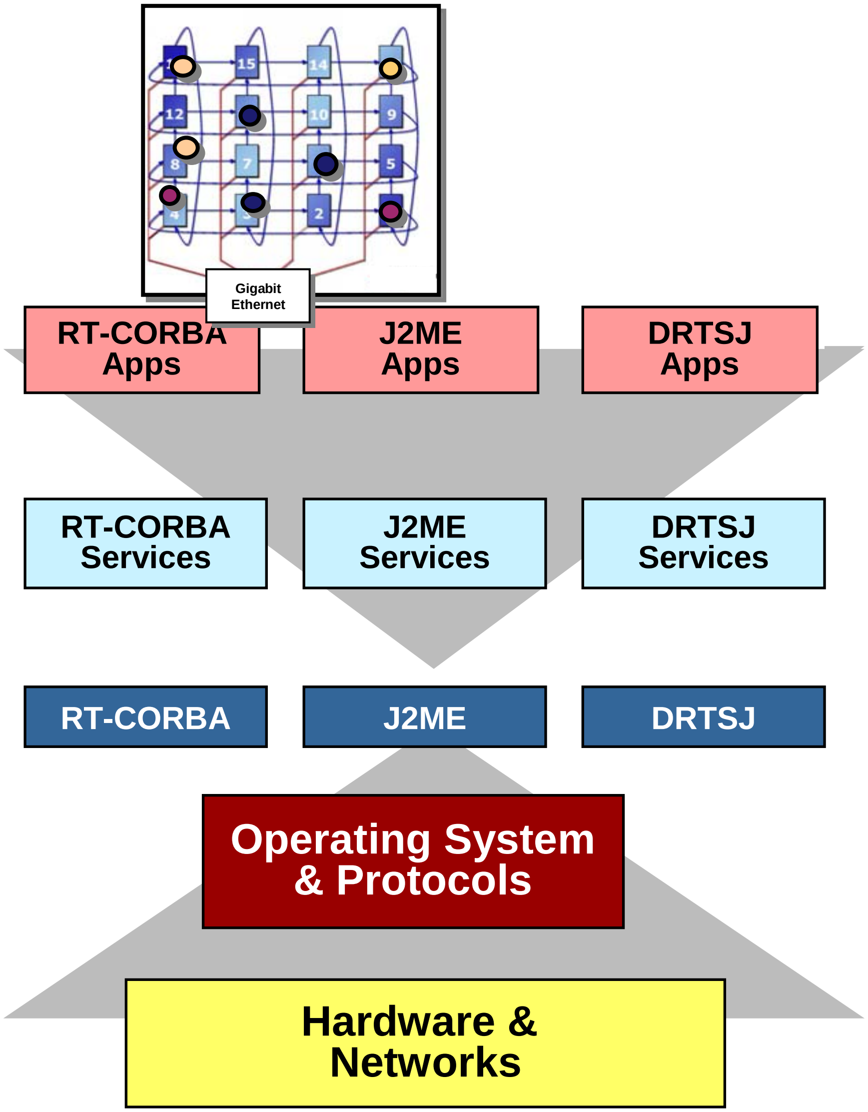
- Limit to how much application functionality can be refactored into reusable COTS middleware
- Middleware itself has become very hard to use & provision statically & dynamically



- Component-based DRE systems are also very hard to deploy & configure
- There are many middleware platform technologies to choose from

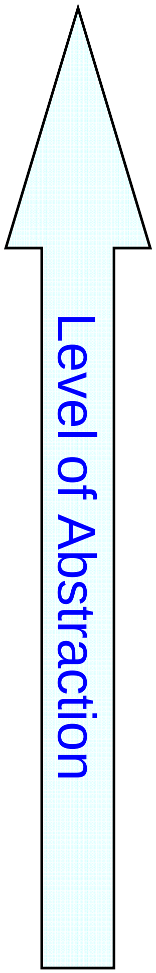
Middleware alone is insufficient to solve key large-scale DRE system challenges!

DRE Systems: The Challenges Ahead

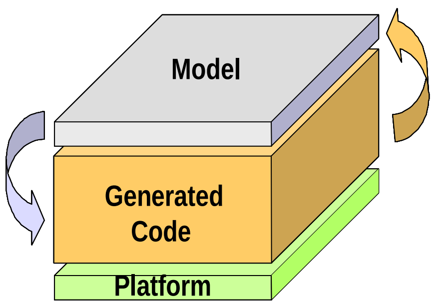


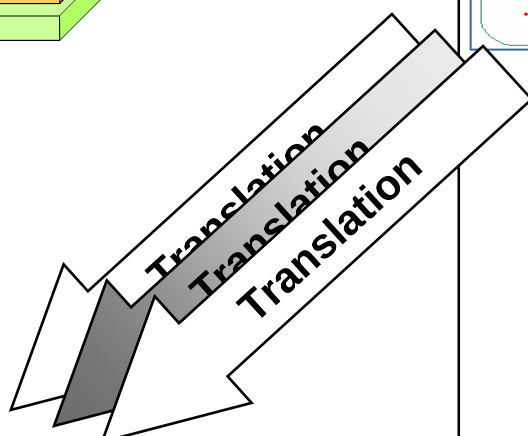
It's enough to make you scream!

Technology Evolution (1/4)



Programming Languages & Platforms





Operating Systems

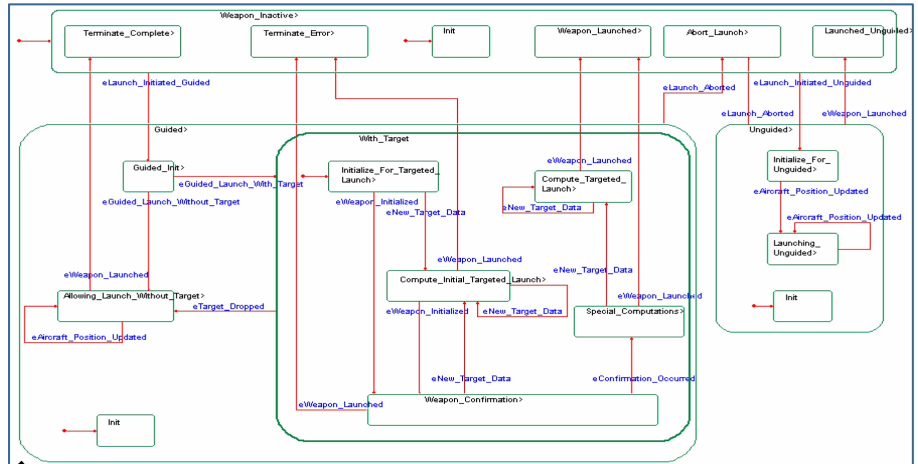
Hardware

C/Fortran

Assembly

Machine code

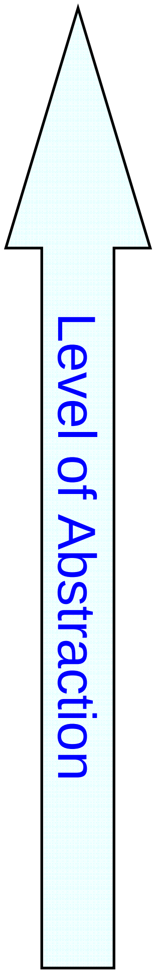
Model-Driven Engineering (MDE)



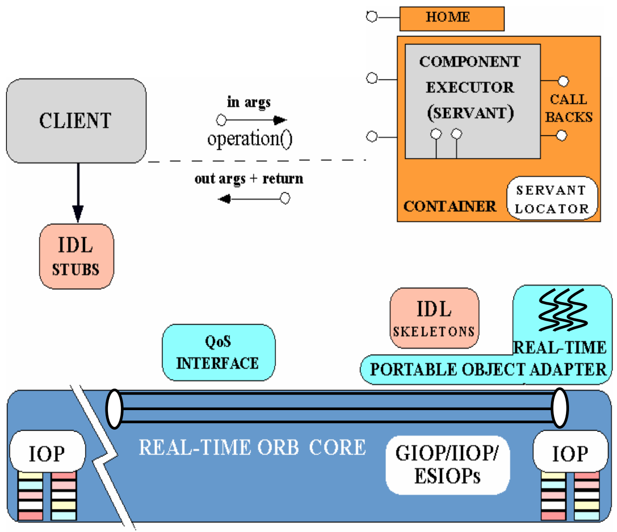
- State chart
- Data & process flow
- Petri Nets

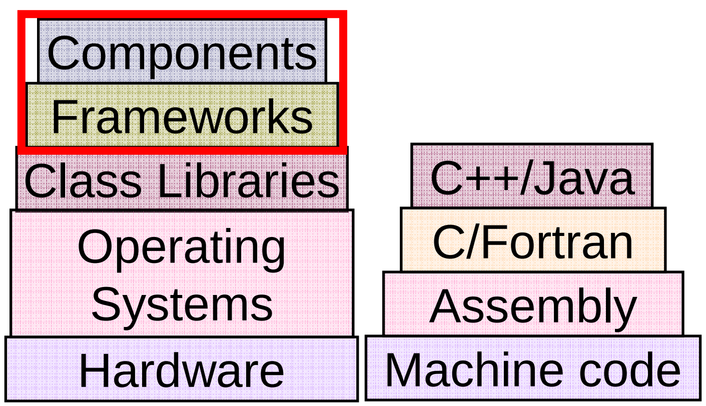
Large Semantic Gap

Technology Evolution (2/4)

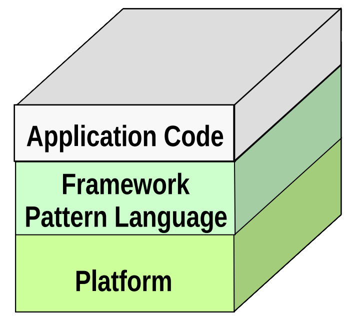


Programming Languages & Platforms





- Newer 3rd-generation languages & platforms have raised abstraction level significantly
  - "Horizontal" platform reuse alleviates the need to redevelop common services



- There are two problems, however:
  - Platform complexity evolved faster than 3rd-generation languages
  - Much application/platform code still (unnecessarily) written manually

Technology Evolution (3/4)

Level of Abstraction

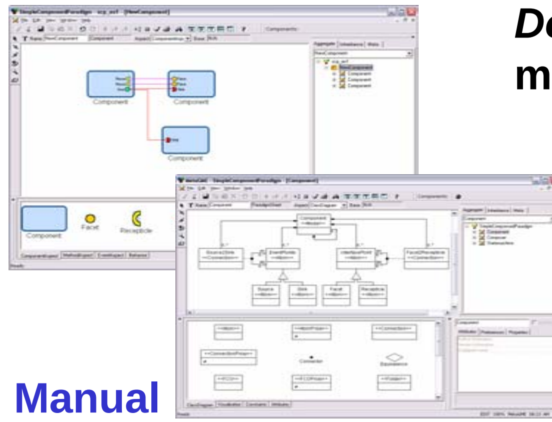
Programming Languages & Platforms

Saturation!!!!

Components
Frameworks
Class Libraries
Operating Systems
Hardware

C++/Java
C/Fortran
Assembly
Machine code

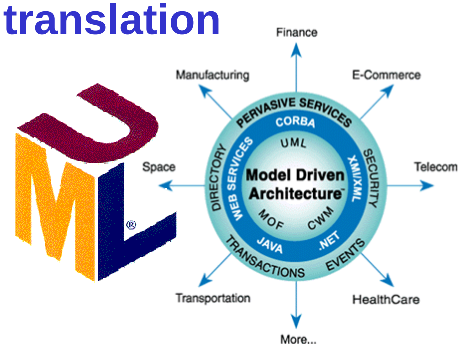
Model-Driven Engineering (MDE)



***Domain-specific* modeling languages**

- ESML
- PICML
- Mathematica
- Excel
- *Metamodels*

Manual translation



Domain-independent modeling languages

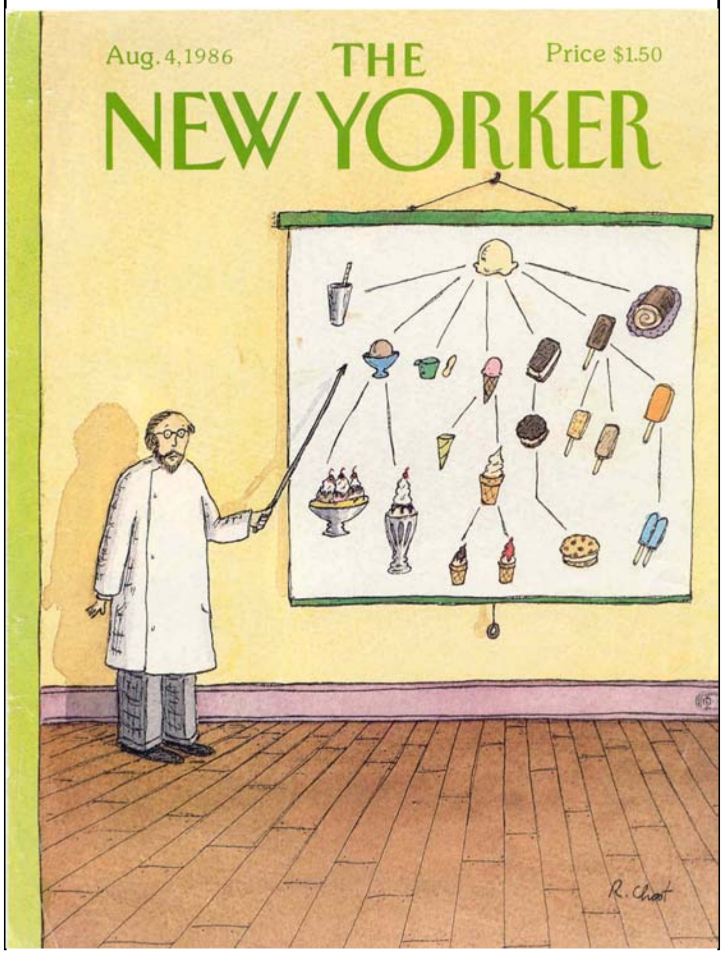
- State Charts
- Interaction Diagrams
- Activity Diagrams

Semi-automated

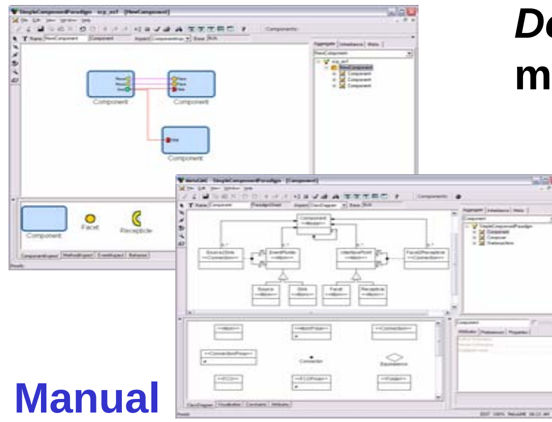
Technology Evolution (3/4)

Level of Abstraction

Programming Languages & Platforms



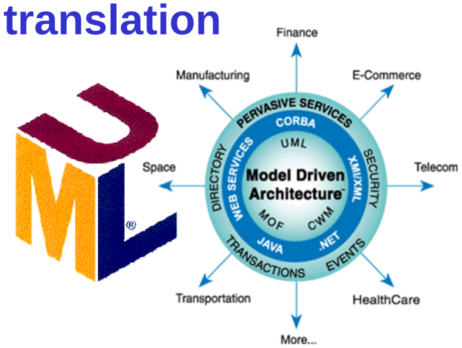
Model-Driven Engineering (MDE)



Manual translation

***Domain-specific* modeling languages**

- ESML
- PICML
- Mathematica
- Excel
- *Metamodels*



Semi-automated

Domain-independent modeling languages

- State Charts
- Interaction Diagrams
- Activity Diagrams

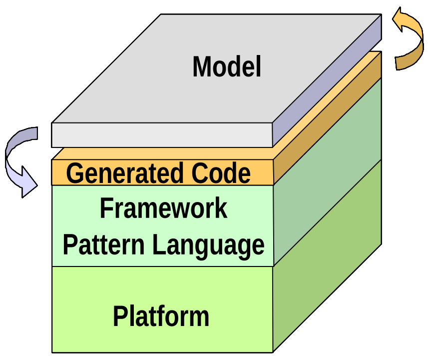
- OMG is evaluating MDE via MIC PSIG
  - mic.omg.org

Model Integrated Computing PSIG

Technology Evolution (3/4)

Level of Abstraction

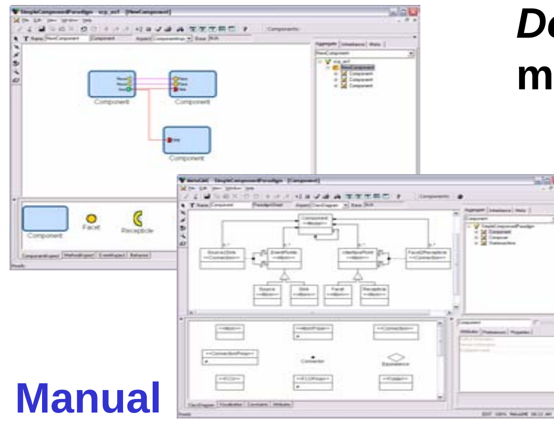
Programming Languages & Platforms



Components
Frameworks
Class Libraries
Operating Systems
Hardware

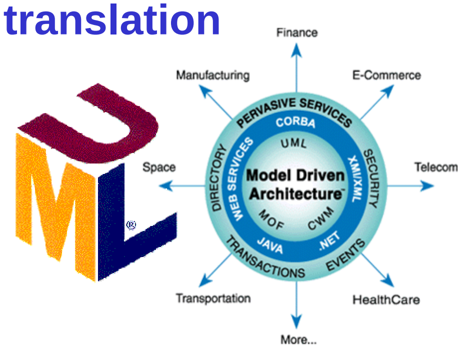
C++/Java
C/Fortran
Assembly
Machine code

Model-Driven Engineering (MDE)



Manual translation

***Domain-specific* modeling languages**
- ESML
- PICML
- Mathematica
- Excel
- *Metamodels*



Semi-automated

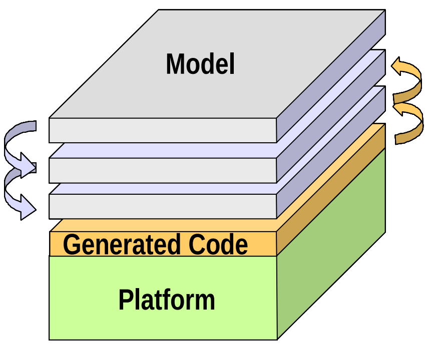
Domain-independent modeling languages
- State Charts
- Interaction Diagrams
- Activity Diagrams

- OMG is evaluating MDE via MIC PSIG
  - mic.omg.org

Technology Evolution (4/4)

Level of Abstraction

Programming Languages & Platforms

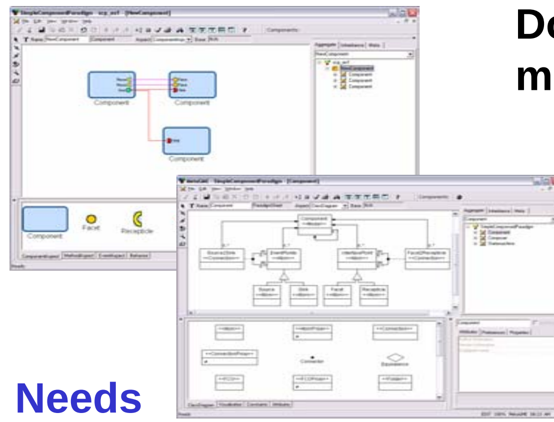


Needs Automation

- Components
- Frameworks
- Class Libraries
- Operating Systems
- Hardware

- C++/Java
- C/Fortran
- Assembly
- Machine code

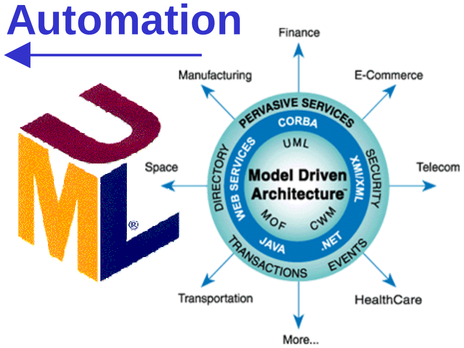
Model-Driven Engineering (MDE)



Domain-specific modeling languages

- ESML
- PICML
- Mathematica
- Excel
- *Metamodels*

Needs Automation



Domain-independent modeling languages

- State Charts
- Interaction Diagrams
- Activity Diagrams

Needs Automation

Research is needed to automate DSMLs & model translators

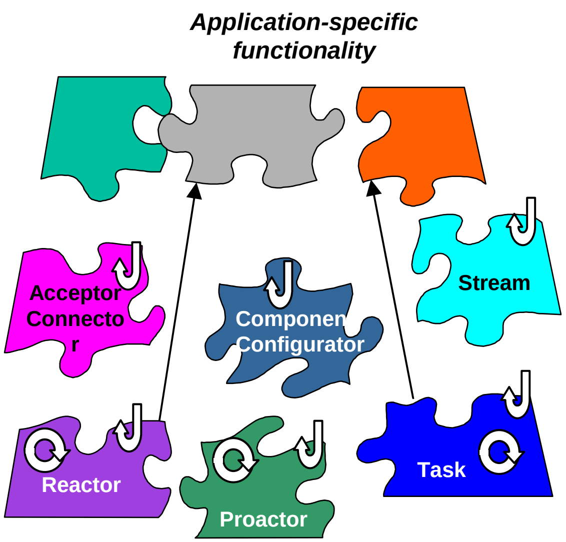
See February 2006 IEEE Computer special issue on MDE techniques & tools

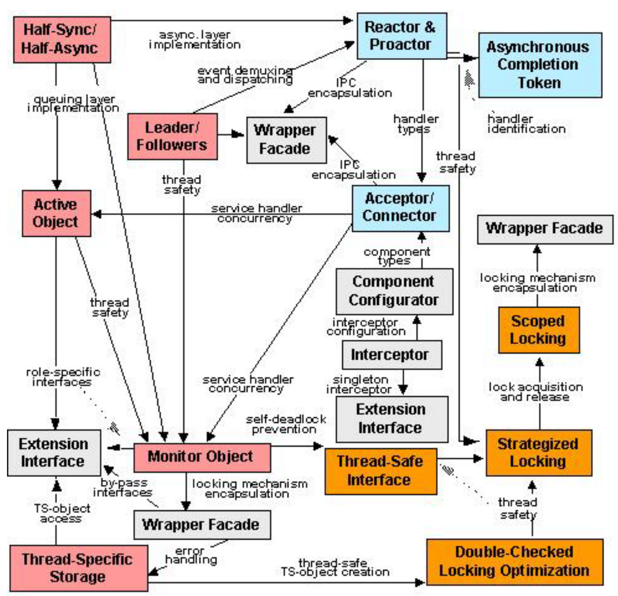
Pattern, Framework, & MDD Synergies

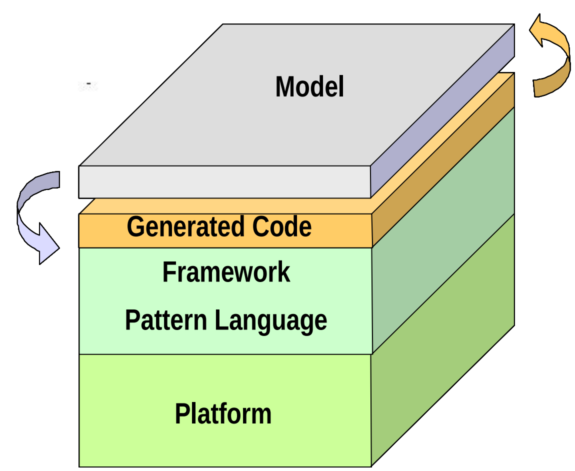
- Frameworks codify expertise in the form of reusable algorithms, component implementations, & extensible architectures

- Patterns codify expertise in the form of reusable architecture design themes & styles, which can be reused event when algorithms, components implementations, or frameworks cannot

- MDE tools codify expertise by automating key aspects of pattern languages & providing developers with domain-specific modeling languages to access the powerful (& complex) capabilities of frameworks



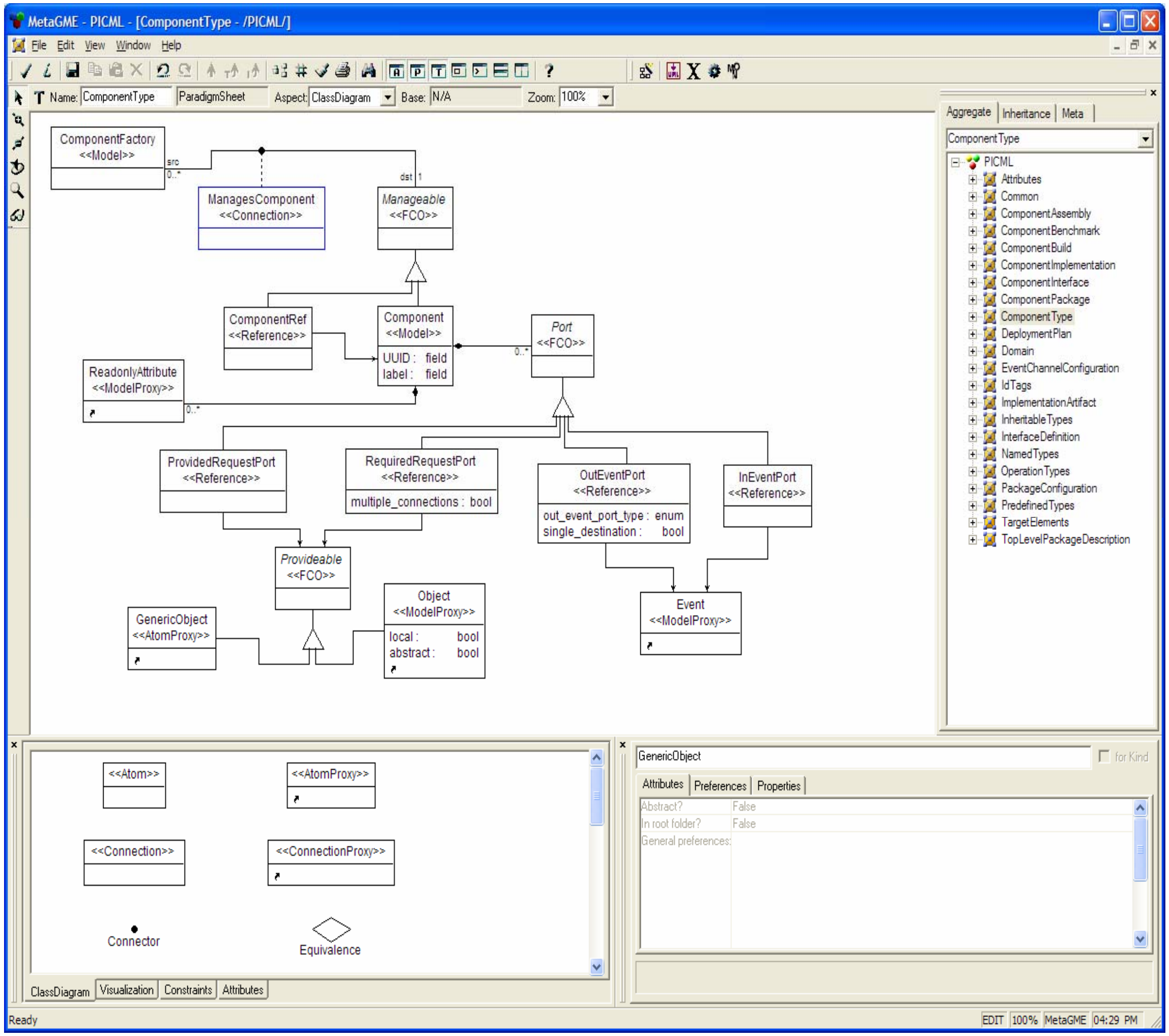




There are now powerful feedback loops advancing these technologies

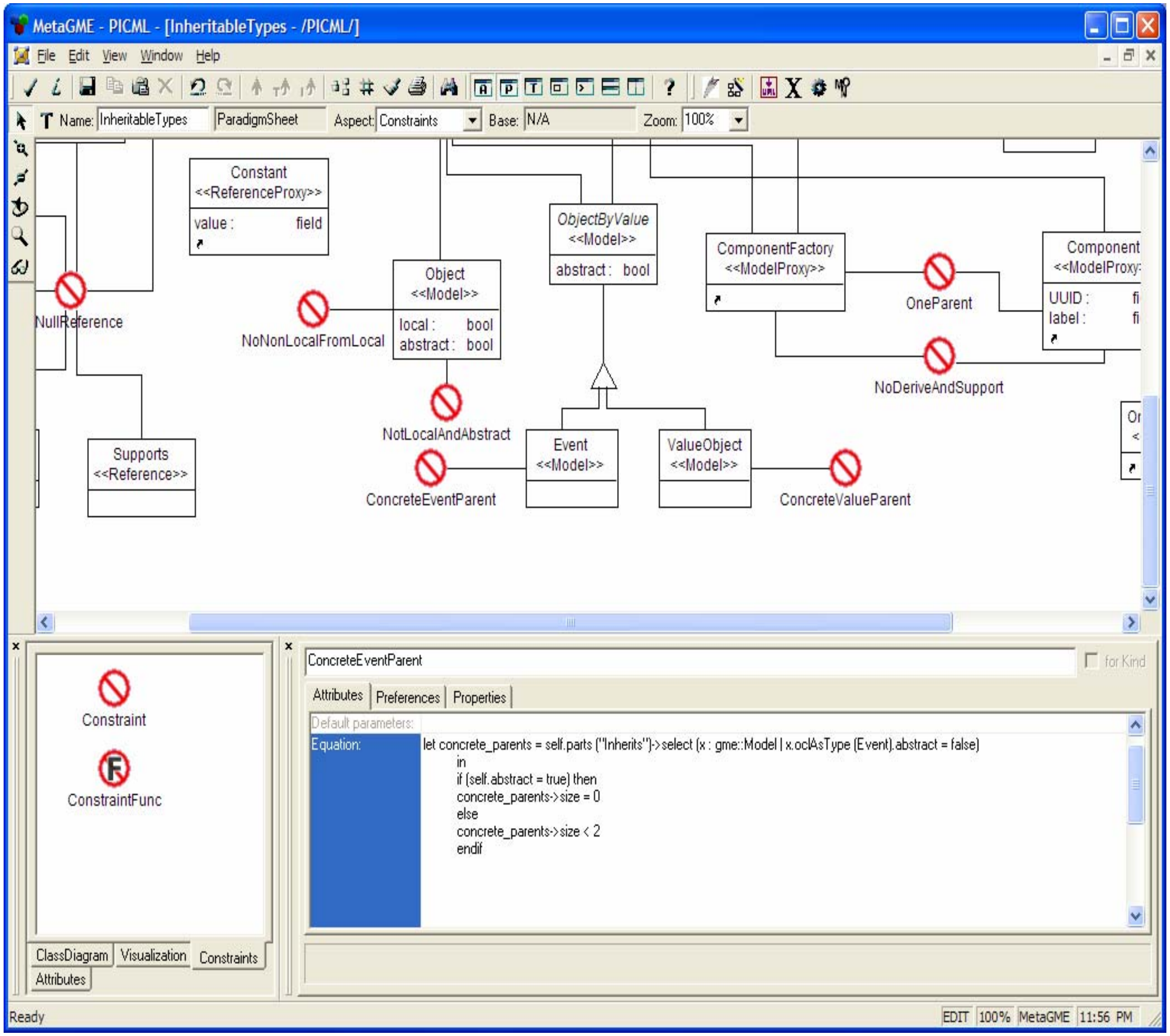
MDD Tool Development in GME

- **Tool developers** use MetaGME to develop a *domain-specific graphical modeling environment*
  - Define syntax & visualization of the environment via *metamodeling*



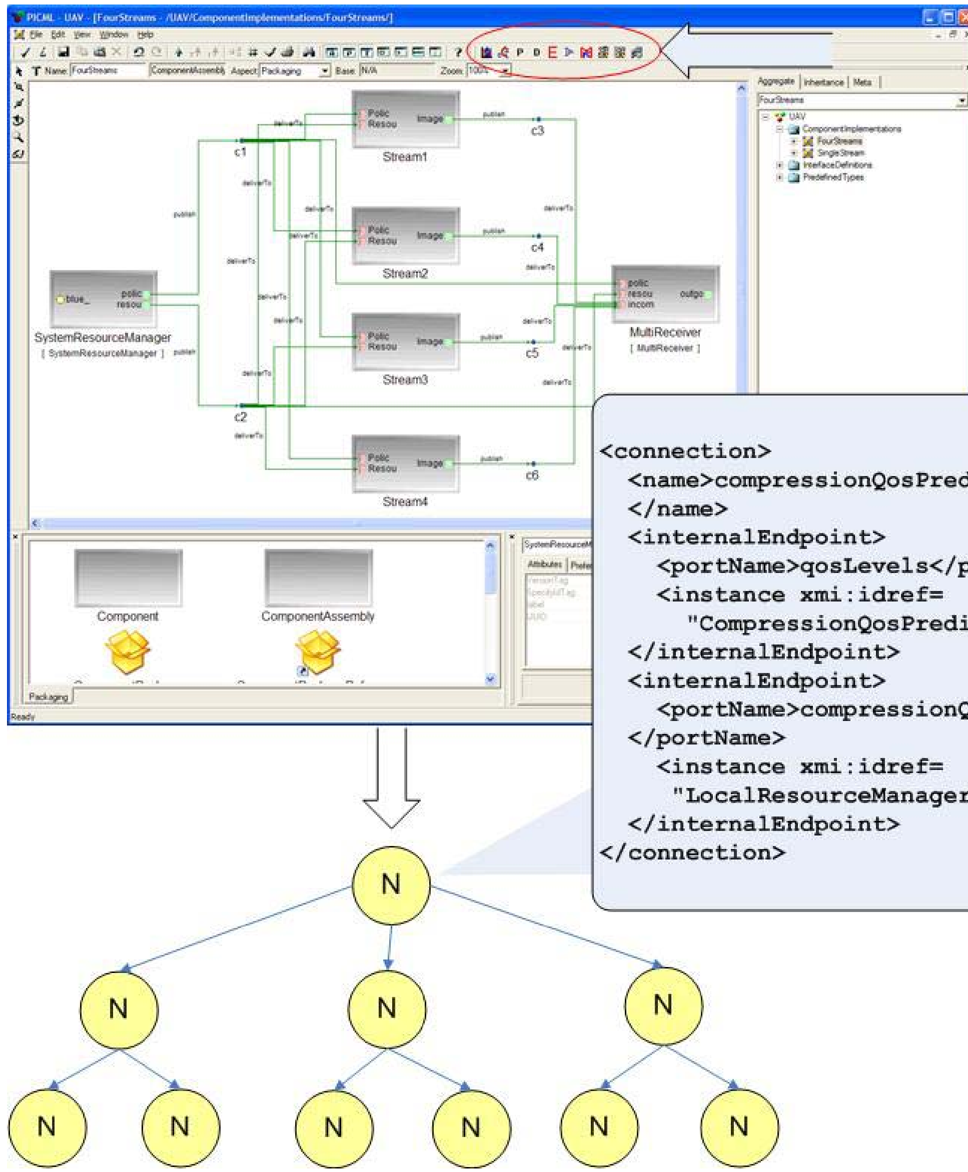
MDD Tool Development in GME

- **Tool developers** use MetaGME to develop a *domain-specific graphical modeling environment*
  - Define syntax & visualization of the environment via *metamodeling*
  - Define static semantics via *Object Constraint Language (OCL)*



MDD Tool Development in GME

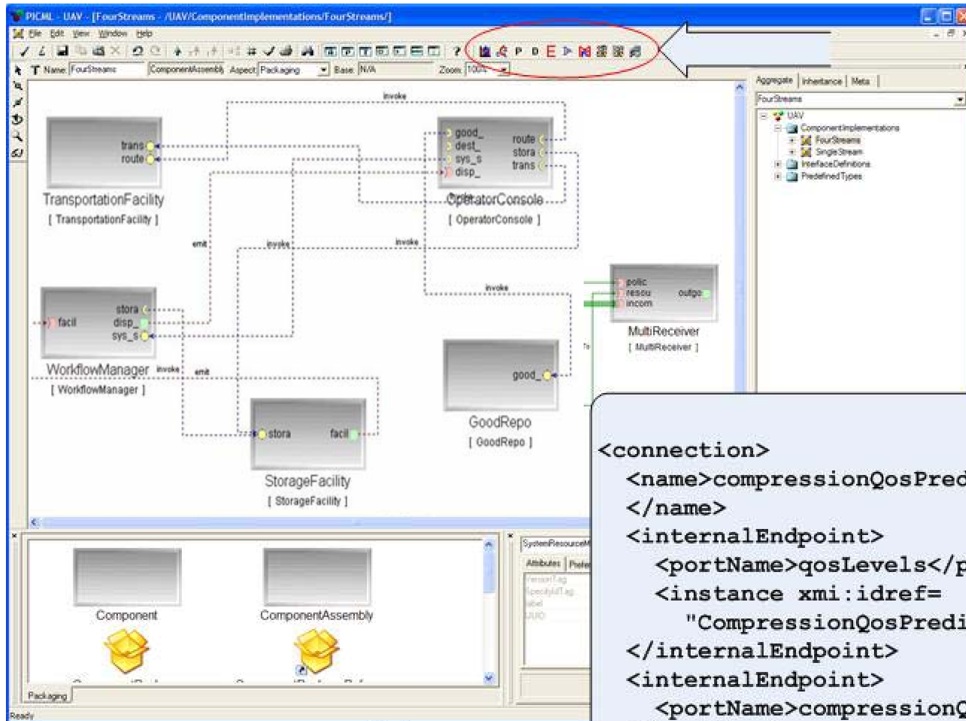
- **Tool developers** use MetaGME to develop a *domain-specific graphical modeling environment*
  - Define syntax & visualization of the environment via *metamodeling*
  - Define static semantics via *Object Constraint Language (OCL)*
  - Dynamic semantics implemented via *model interpreters*



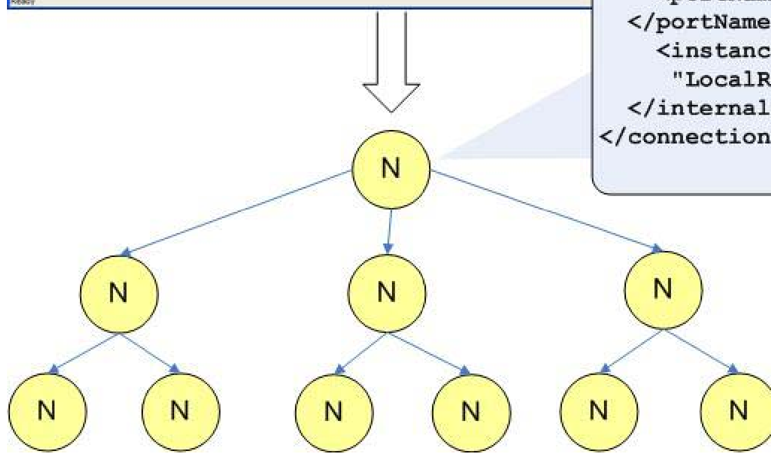

```
<connection>
  <name>compressionQosPredictor_qosLevels
  </name>
  <internalEndpoint>
    <portName>qosLevels</portName>
    <instance xmi:idref=
      "CompressionQosPredictor"/>
  </internalEndpoint>
  <internalEndpoint>
    <portName>compressionQosPredictor
  </portName>
    <instance xmi:idref=
     "LocalResourceManagerComponent"/>
  </internalEndpoint>
</connection>
```

MDD Tool Development in GME

- **Tool developers** use MetaGME to develop a *domain-specific graphical modeling environment*
  - Define syntax & visualization of the environment via *metamodeling*
  - Define static semantics via *Object Constraint Language (OCL)*
  - Dynamic semantics implemented via *model interpreters*

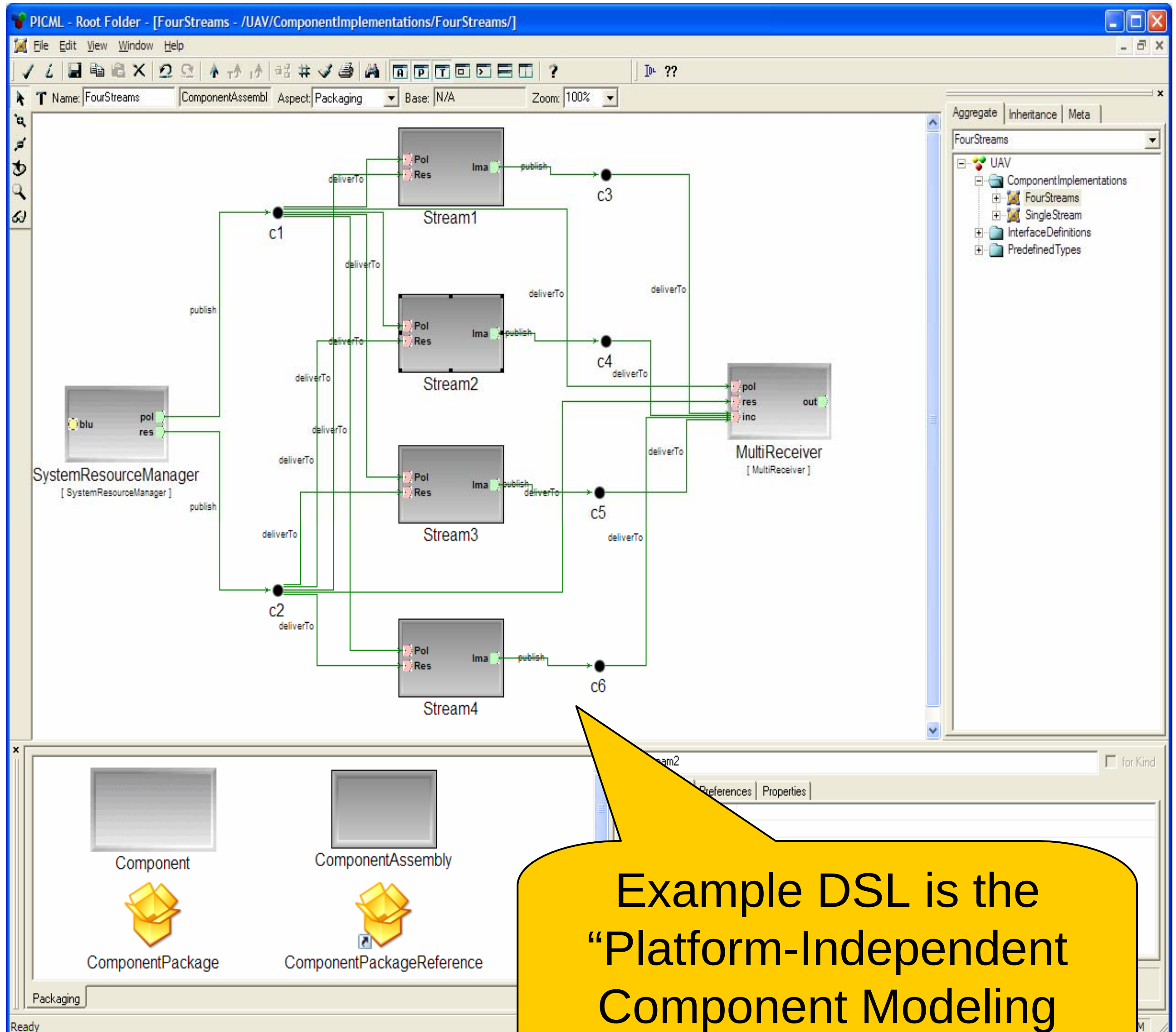



```
<connection>
  <name>compressionQosPredictor_qosLevels
  </name>
  <internalEndpoint>
    <portName>qosLevels</portName>
    <instance xmi:idref=
      "CompressionQosPredictor"/>
  </internalEndpoint>
  <internalEndpoint>
    <portName>compressionQosPredictor
  </portName>
    <instance xmi:idref=
     "LocalResourceManagerComponent"/>
  </internalEndpoint>
</connection>
```



MDD Application Development with GME

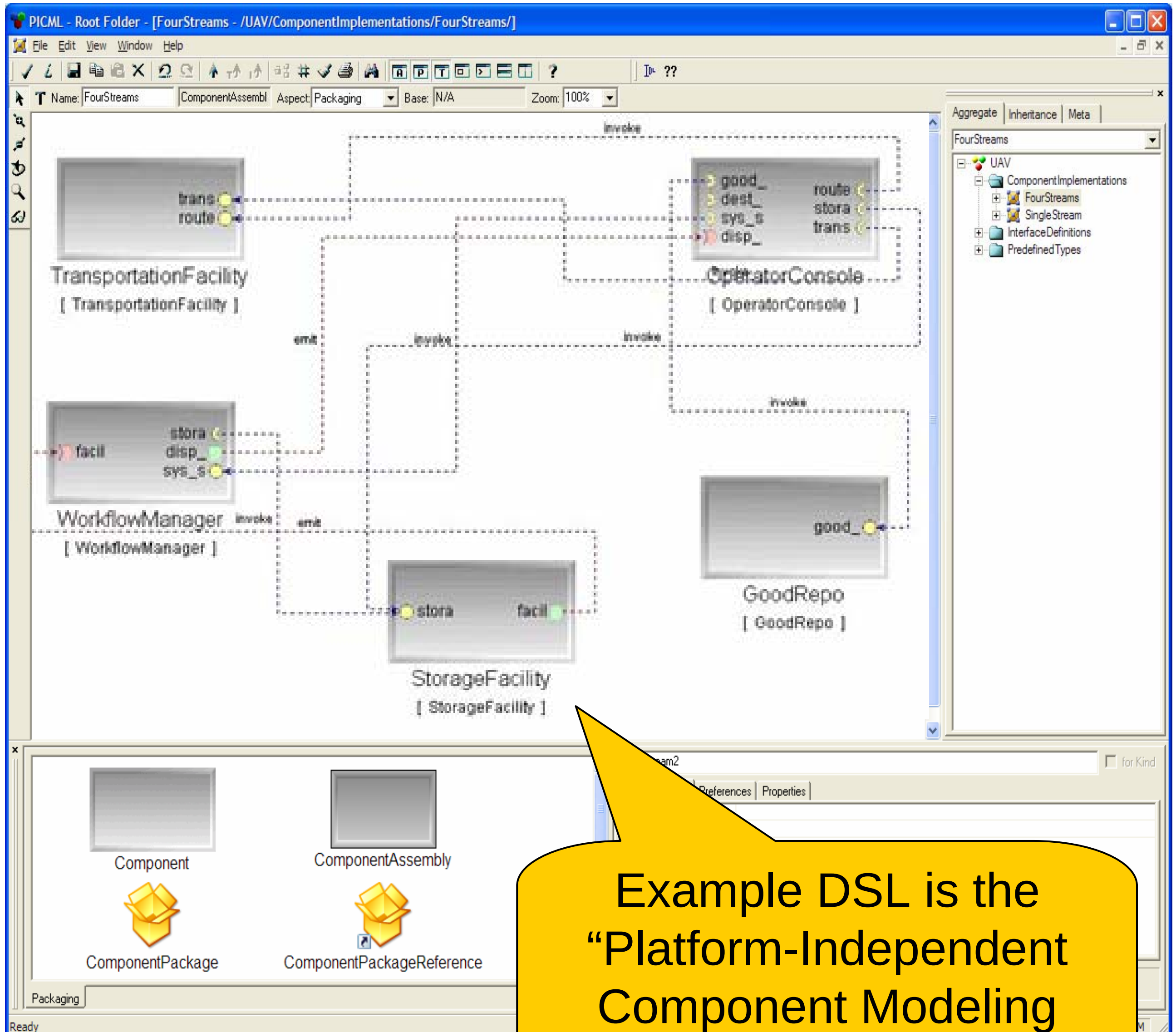
- **Application developers** use modeling environments created w/MetaGME to build *applications*
  - Capture elements & dependencies visually



Example DSL is the "Platform-Independent Component Modeling Language" (PICML) tool

MDD Application Development with GME

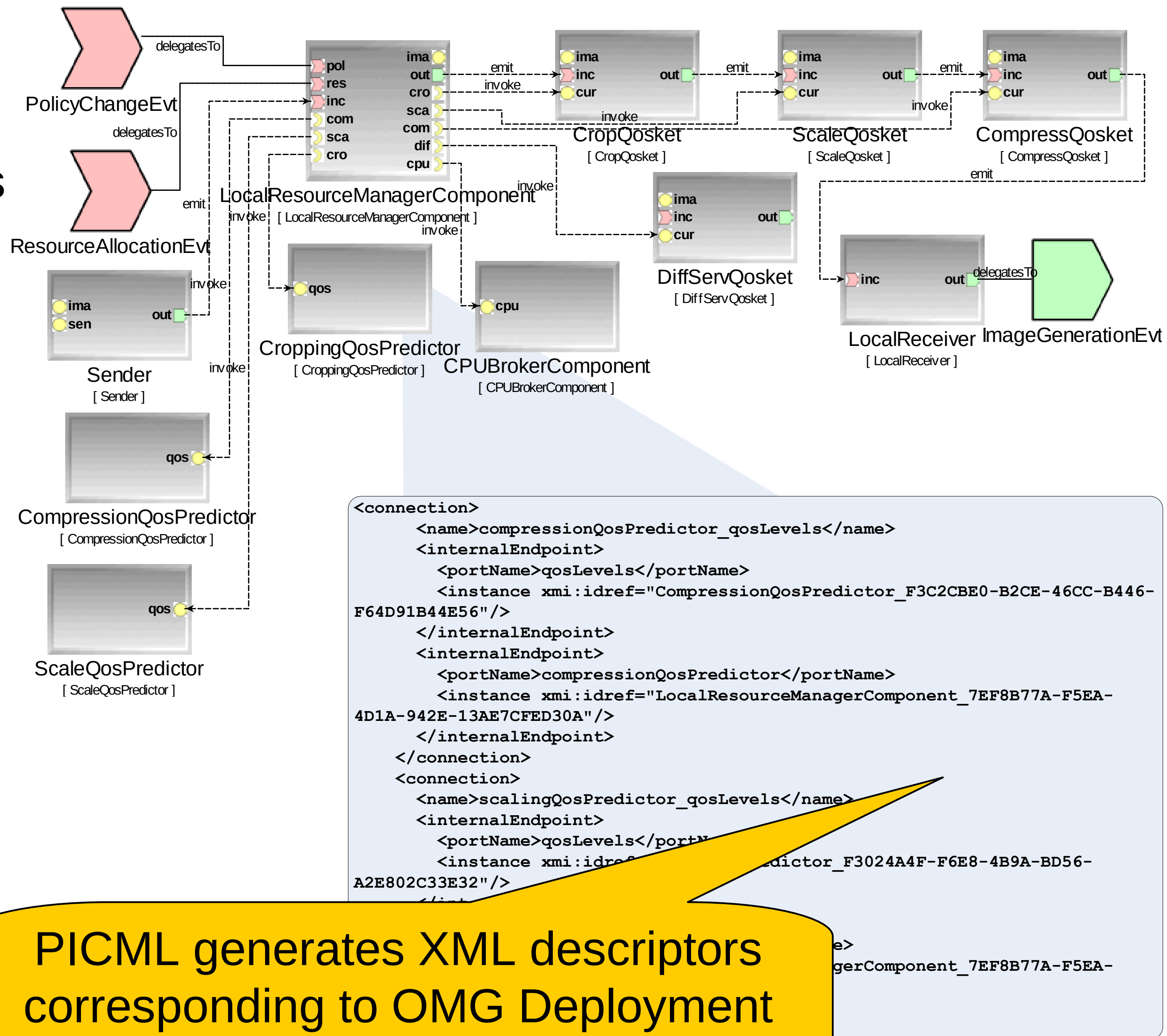
- **Application developers** use modeling environments created w/MetaGME to build *applications*
  - Capture elements & dependencies visually



Example DSL is the "Platform-Independent Component Modeling Language" (PICML) tool

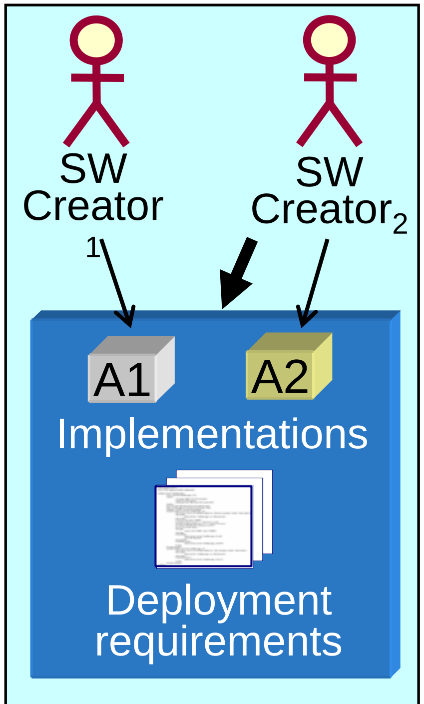
MDD Application Development with GME

- **Application developers** use modeling environments created w/MetaGME to build *applications*
  - Capture elements & dependencies visually
  - Model interpreter produces something useful from the models
    - e.g., 3rd generation code, simulations, deployment descriptions & configurations



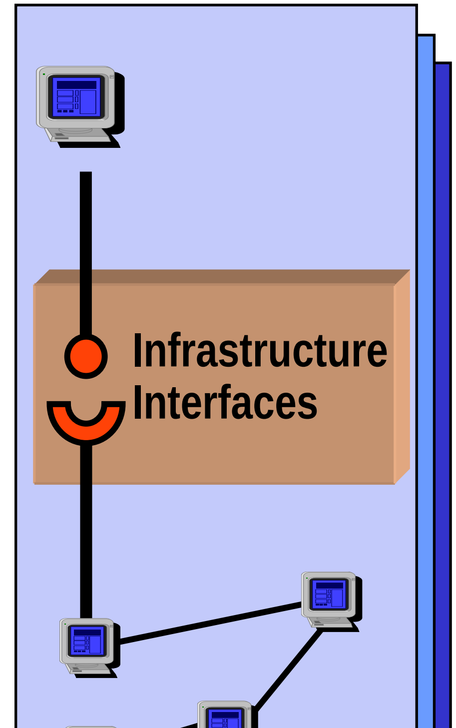
PICML generates XML descriptors corresponding to OMG Deployment & Configuration (D&C) specification

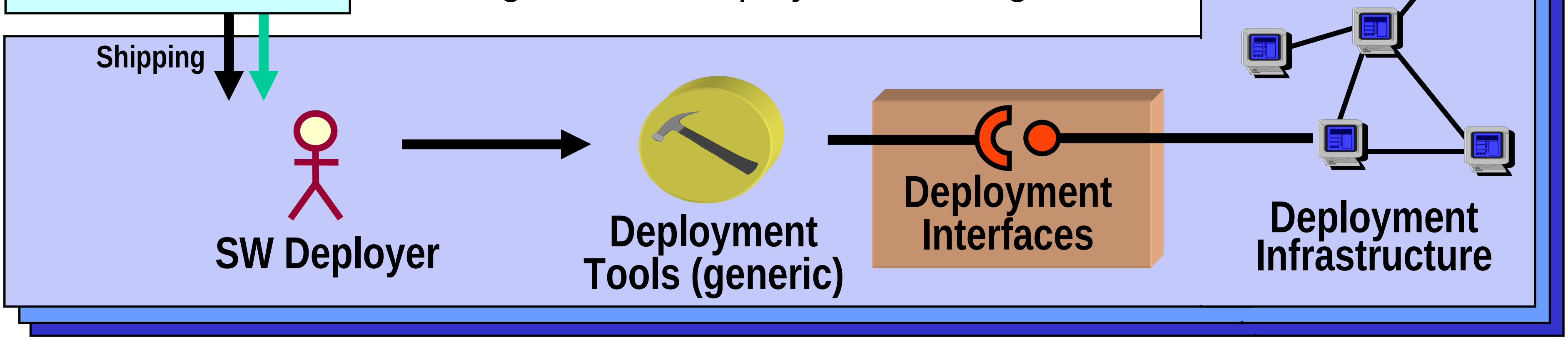
OMG Component Deployment & Configuration



Goals of D&C Phase

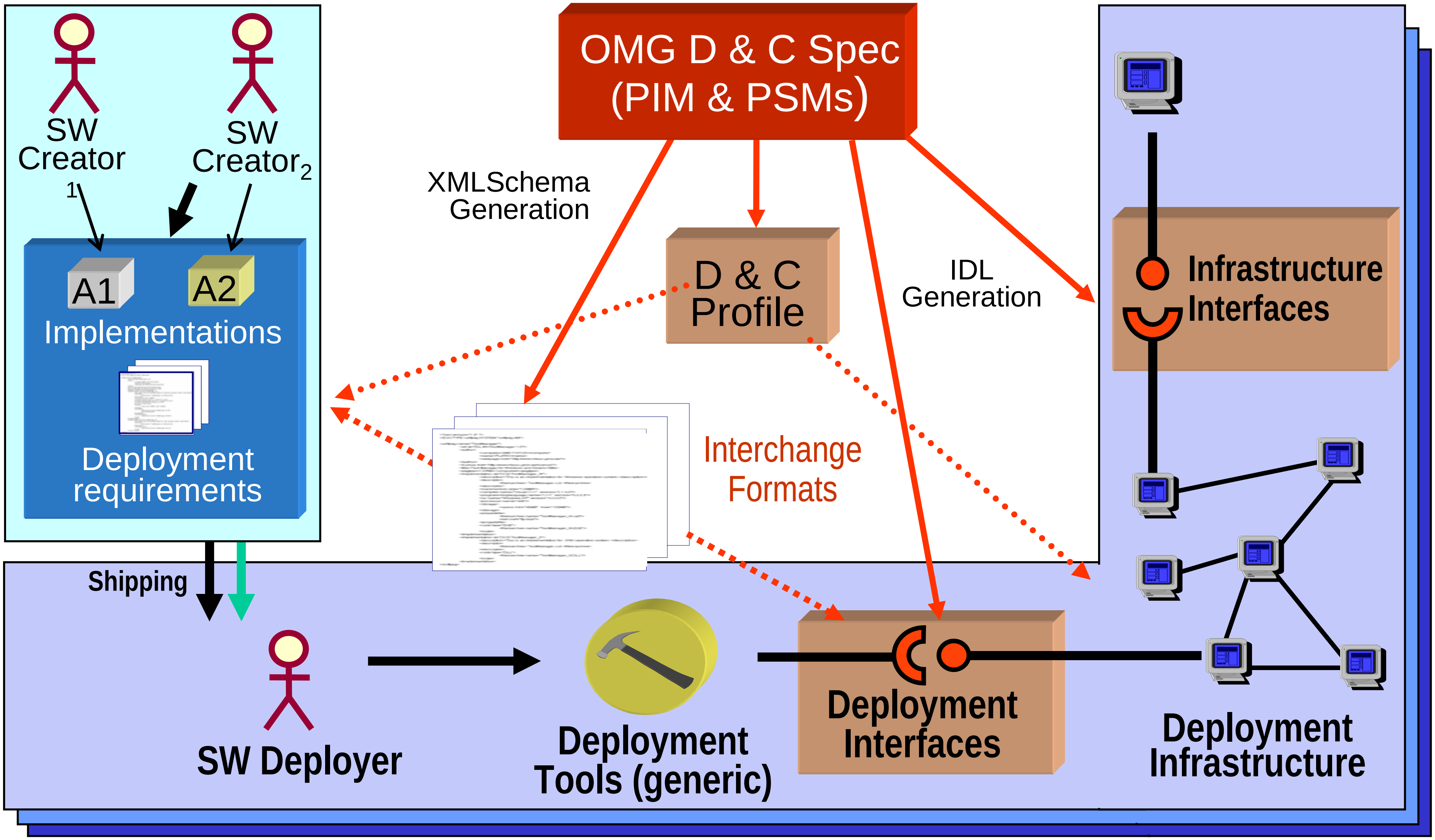
- Promote component reuse
- Build complex applications by assembling existing components
- Automate common services configuration
- Declaratively inject QoS policies into applications
- Dynamically deploy components to target heterogeneous domains
- Optimize systems based on component configuration & deployment settings





OMG Deployment & Configuration (D&C) specification (ptc/05-01-07)

OMG Component Deployment & Configuration



OMG Deployment & Configuration (D&C) specification (ptc/05-01-07)

MDD Example: OMG Deployment & Configuration

Specification & Implementation

- Defining, partitioning, & implementing app functionality as standalone components

Packaging

- Bundling a suite of software binary modules & metadata representing app components

Installation

- Populating a repository with packages required by app

Configuration

- Configuring packages with appropriate parameters to satisfy functional & systemic requirements of an application without constraining to physical resources

Planning

- Making deployment decisions to identify nodes in target environment where packages will be deployed

Preparation

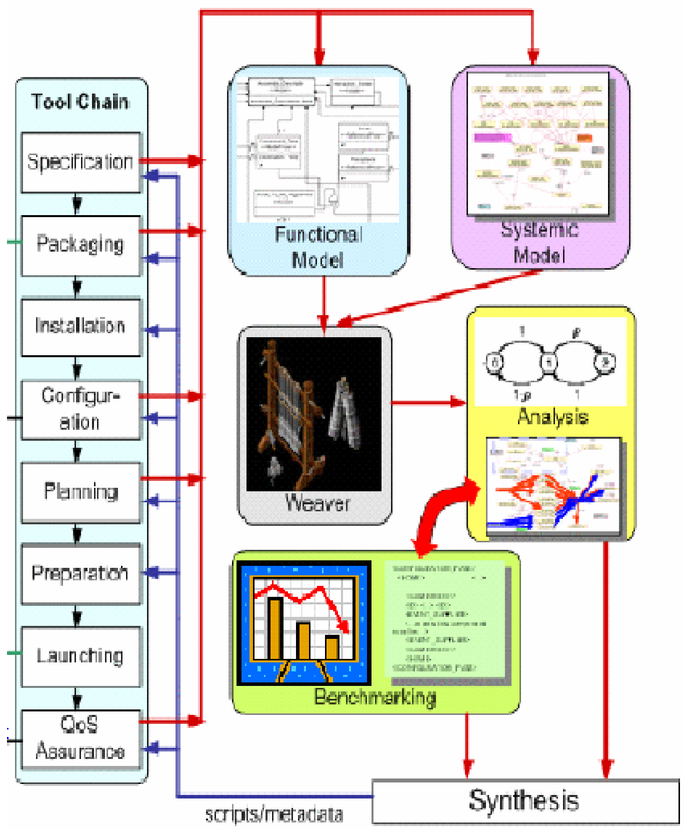
- Moving binaries to identified entities of target environment

Launching

- Triggering installed binaries & bringing app to ready state

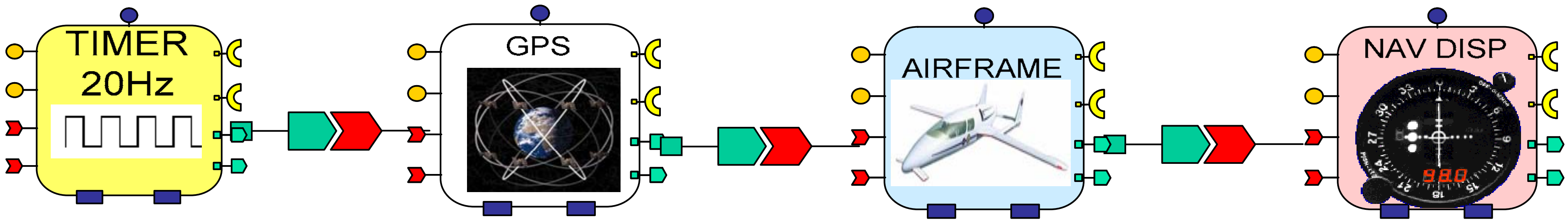
QoS Assurance & Adaptation

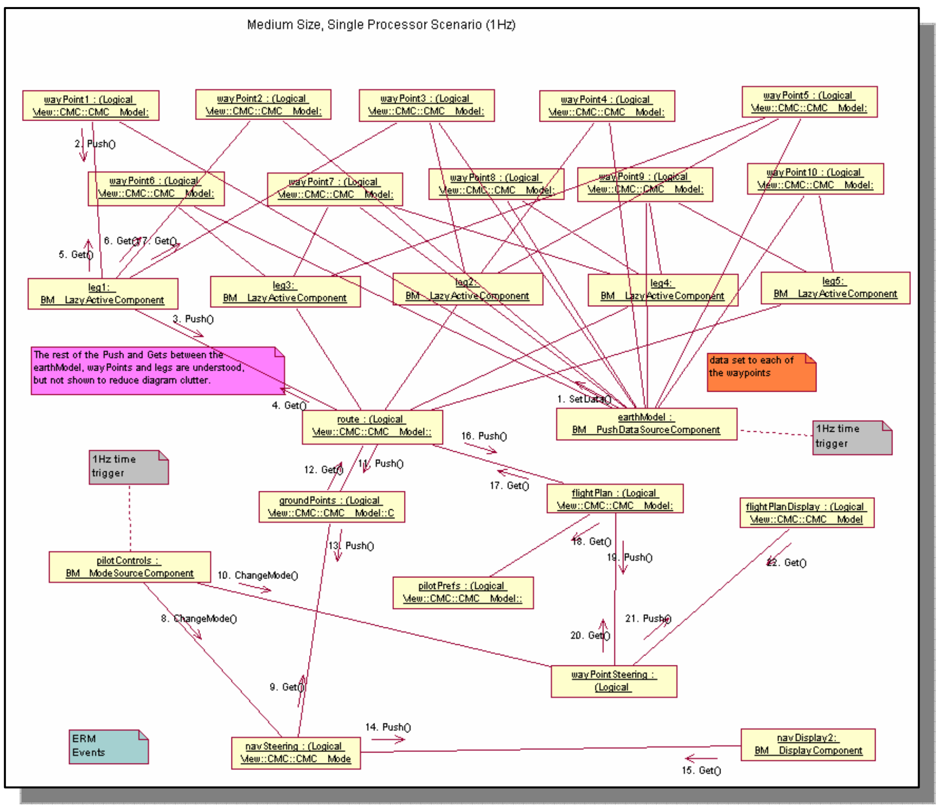
- Runtime (re)configuration & resource management to maintain end-to-end QoS



OMG Deployment & Configuration (D&C) specification (ptc/05-01-07)

Challenge 1: The Packaging Aspect

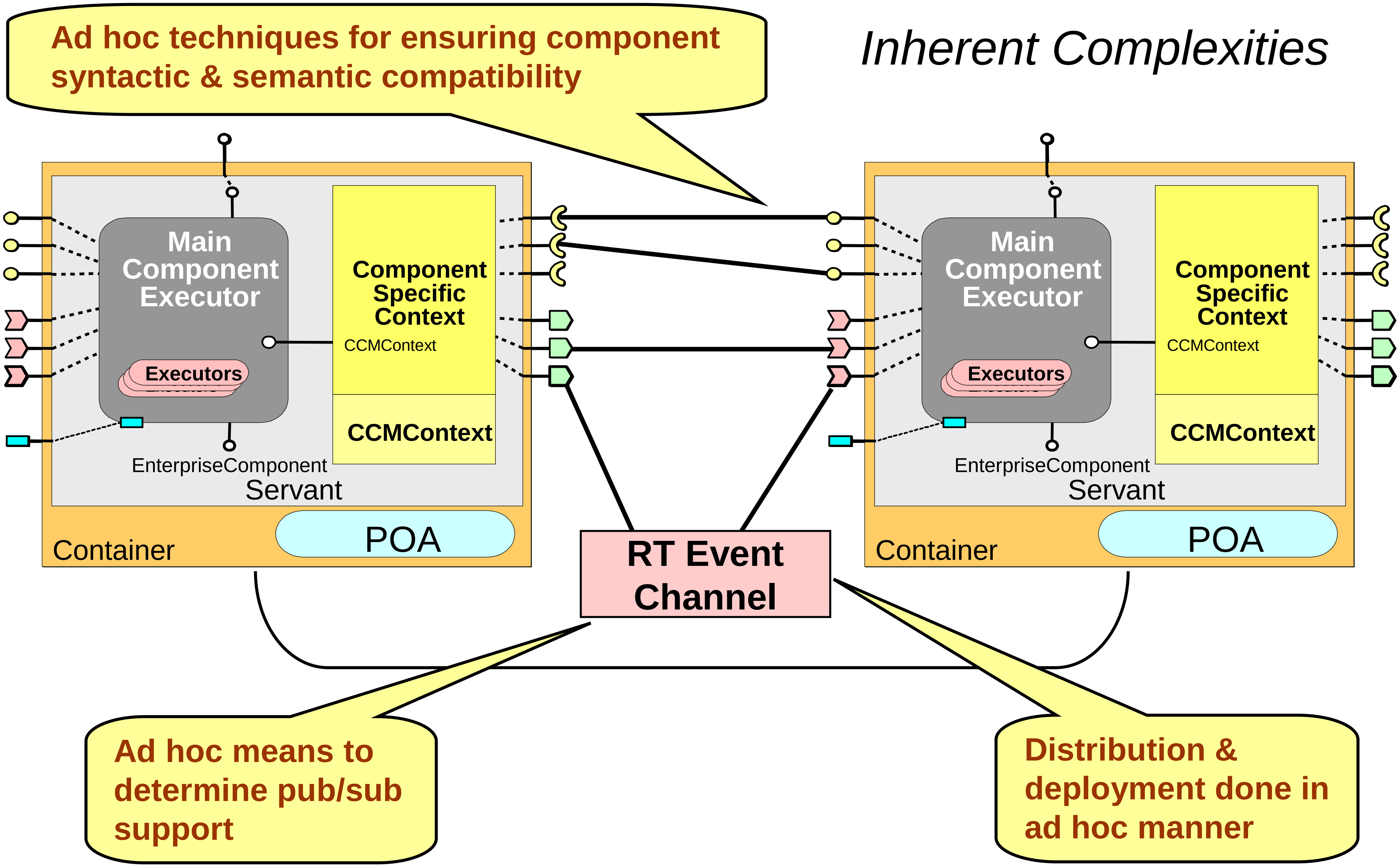




- Application components are bundled together into *assemblies*
- Several different assemblies tailored towards delivering different end-to-end QoS and/or using different algorithms can be part of the package
  - e.g., large-scale DRE systems require 100s-1,000s of components
- Packages describing the components & assemblies can be scripted via XML descriptors

Packaging Aspect Problems (1/2)

Inherent Complexities



Packaging Aspect Problems (2/2)

Accidental Complexities

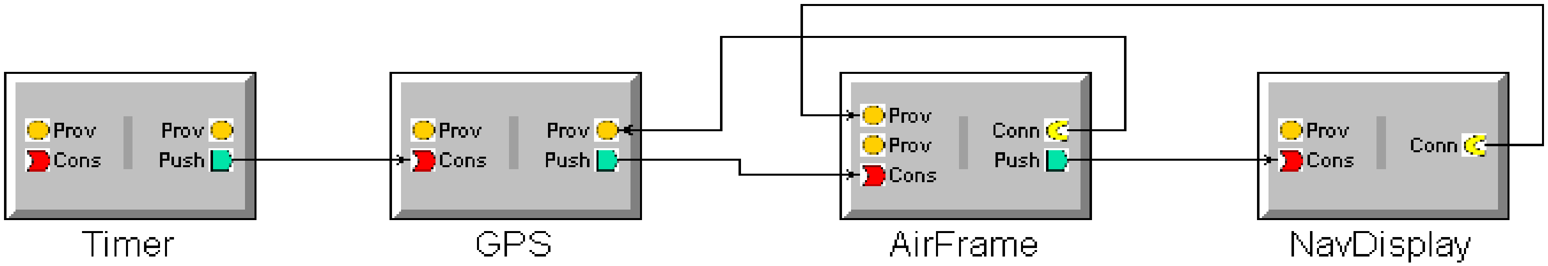
```
<!– Associate components with impls -->
<assemblyImpl>
  <instance xmi:id="RateGen">
    <name>RateGen Subcomponent</name>
    <package href="RateGen.cpd"/>
  </instance>
  <instance xmi:id="GPS">
    <name>GPS Subcomponent</name>
    <package href="GPS.cpd"/>
  </instance>
  <instance xmi:id="NavDisplay">
    <name>NavDisplay Subcomponent</name
    <package href="NavDisplay.cpd"/>
  </instance>
 </assemblyImpl>
```

Existing practices involve handcrafting XML descriptors

XML file in excess of 3,000 lines, even for medium sized scenarios

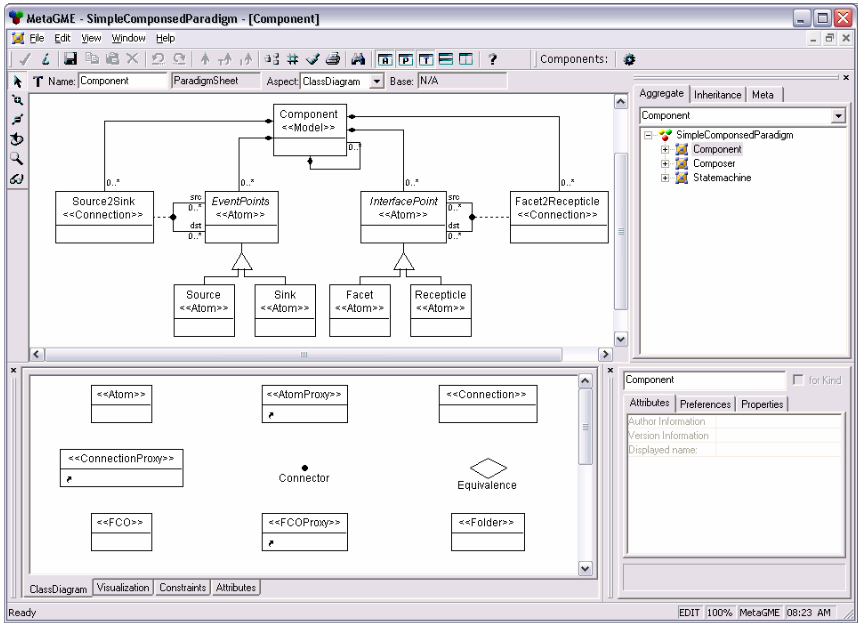
Modifications to the assemblies requires modifying XML file

MDD Solution for Packaging Aspect



Approach:

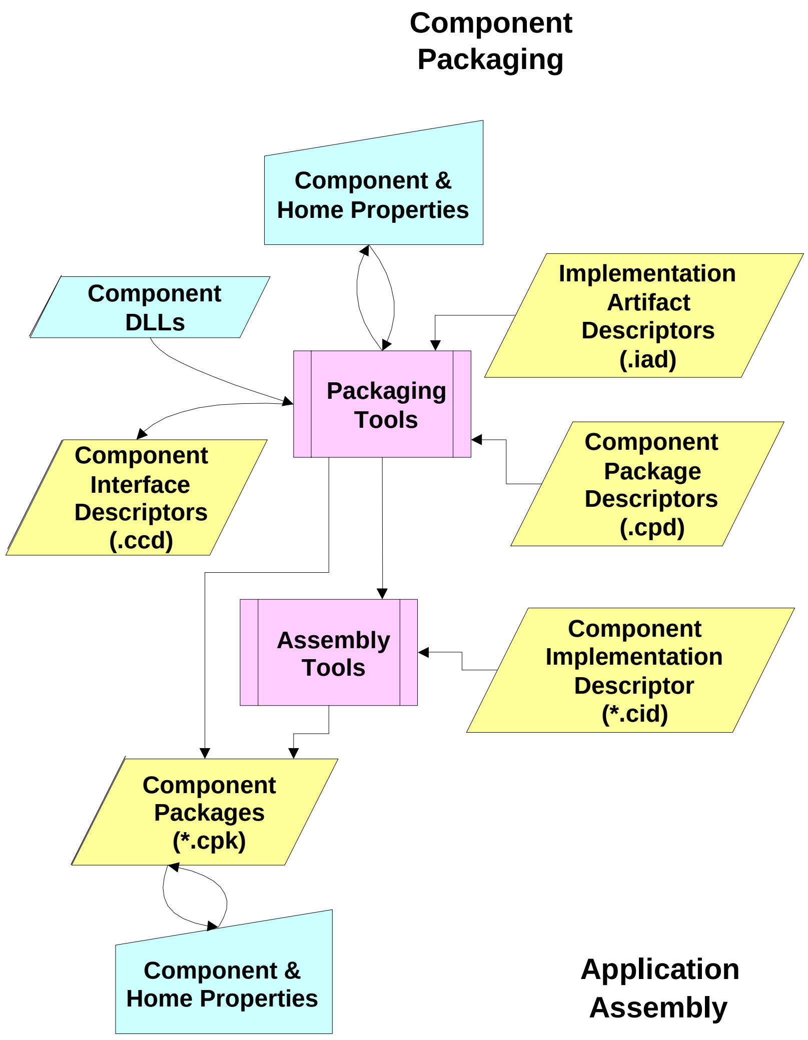
- Develop a ***Platform-Independent Component Modeling Language* (PICML)** to address inherent & accidental complexities of packaging
  - Capture dependencies visually
  - Define semantic constraints using Object Constraint Language (OCL)
  - Generate domain-specific metadata from models
  - Correct-by-construction
- PICML is developed using Generic Modeling Environment (GME)



www.cs.wustl.edu/~schmidt/PDF/RTAS-PICML.pdf

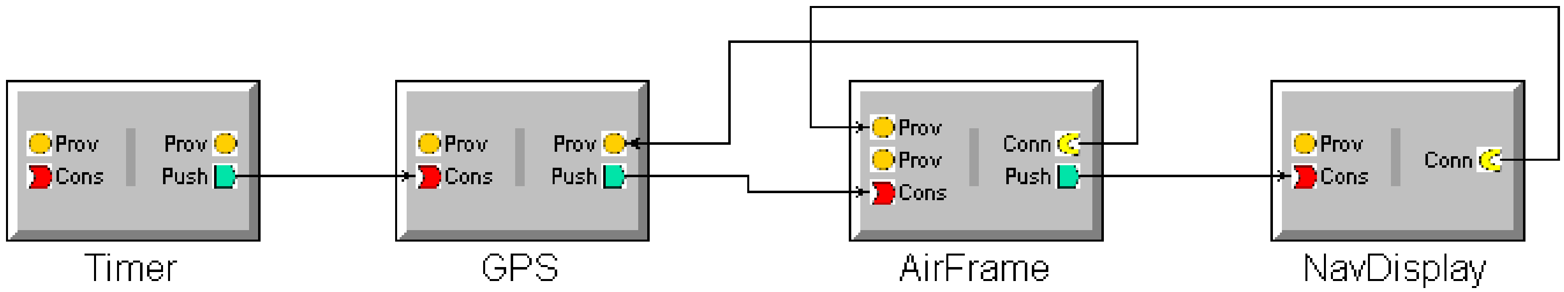
Example Metadata Generated by PICML

- **Component Interface Descriptor (.ccd)**
  - Describes the interface, ports, properties of a single component
- **Implementation Artifact Descriptor (.iad)**
  - Describes the implementation artifacts (e.g., DLLs, OS, etc.) of one component
- **Component Package Descriptor (.cpd)**
  - Describes multiple alternative implementations of a single component
- **Package Configuration Descriptor (.pcd)**
  - Describes a configuration of a component package
- **Top-level Package Descriptor (package.tpd)**
  - Describes the top-level component package in a package (.cpk)
- **Component Implementation Descriptor (.cid)**
  - Describes a specific implementation of a component interface
  - Implementation can be either monolithic- or assembly-based
  - Contains sub-component instantiations in case of assembly based implementations
  - Contains inter-connection information between components
- **Component Packages (.cpk)**
  - A component package can contain a single component
  - A component package can also contain an assembly



Based on OMG (D&C) specification (ptc/05-01-07)

Example Output from PICML Model



A Component Implementation Descriptor (*.cid) file

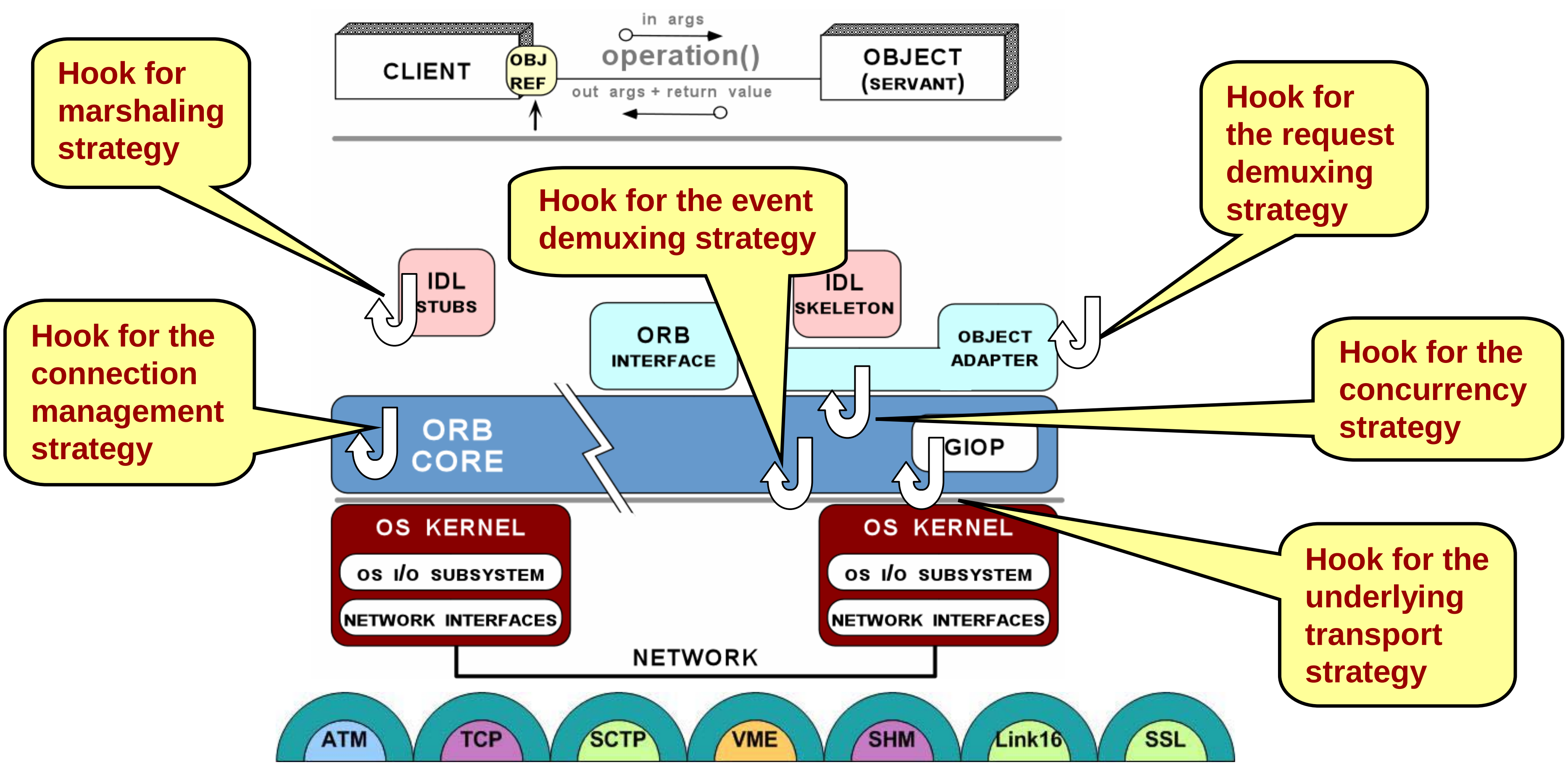
- Describes a specific implementation of a component interface
- Describes component interconnections

```
<monolithicImpl> [...]
  <deployRequirement>
    <name>GPS</name>
    <resourceType>GPS Device</resourceType>
    <property><name>vendor</name>
      <value>
        <type> <kind>tk_string</kind> </type>
        <value> <string>My GPS Vendor</string>
      </value>
    </property>
  </deployRequirement>
  [... Requires Windows OS ...]
</monolithicImpl>
```

```
<connection> <name>GPS Trigger</name>
    <internalEndpoint>  <portName>Pulse</portName>
      <instance href="#RateGen"/>
    </internalEndpoint>
    <internalEndpoint> <portName>Refresh</portName>
      <instance href="#GPS"/>
    </internalEndpoint>
  </connection>
  <connection> <name>NavDisplay Trigger</name>
    <internalEndpoint> <portName>Ready</portName>
      <instance href="#GPS"/>
    </internalEndpoint>
    <internalEndpoint> <portName>Refresh</portName>
      <instance href="#NavDisplay"/>
    </internalEndpoint>
  </connection>
```

Challenge 2: The Configuration Aspect

Component middleware is characterized by a large *configuration space* that maps known variations in the application requirements space to known variations in the middleware solution space

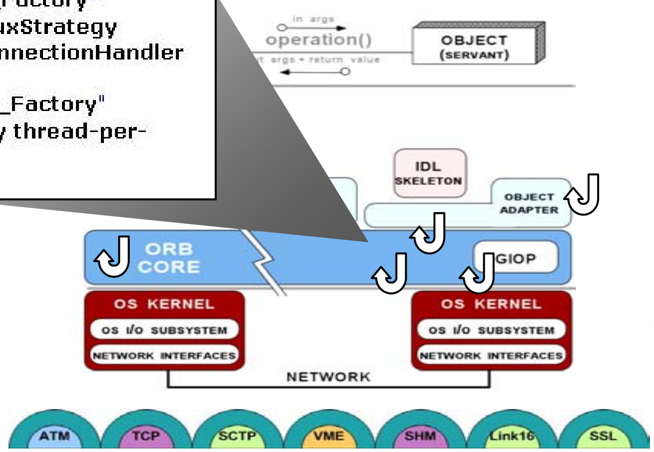


Configuration Aspect Problems

Middleware developers

- Documentation & capability synchronization
- Semantic constraints & QoS evaluation of specific configurations

```
ests/Latency/Thread_Per_Connection/svc.conf
ACE_Svc_Conf>
 <!--      -->
 <!--   $Id: svc.conf.xml,v 1.1 2002/08/23
 22:23:04 nanbor Exp $   -->
 <!--      -->
 <static id="Advanced_Resource_Factory"
   params="-ORBReactorType select_mt -
   ORBReactorMaskSignals 0 -
   ORBFlushingStrategy blocking" />
 <static id="Client_Strategy_Factory"
   params="-ORBTransportMuxStrategy
   EXCLUSIVE -ORBClientConnectionHandler
   RW" />
 <static id="Server_Strategy_Factory"
   params="-ORBConcurrency thread-per-
   connection" />
/ACE_Svc_Conf>
```



Application developers

- Must understand middleware constraints & semantics
  - Increases accidental complexity
- Different middleware uses different configuration mechanisms

Microsoft .net — XML Configuration Files

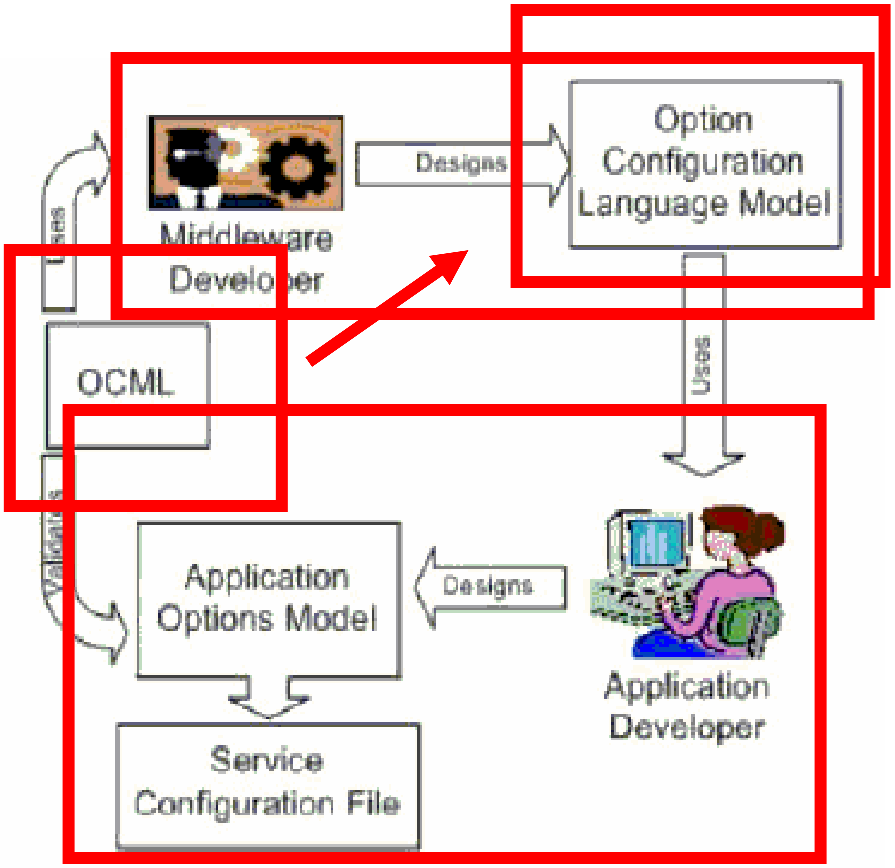
JAVA — XML Property Files

CORBA — CIAO/CCM provides ~500 configuration options

MDD Solutions for Configuration Aspect

Approach:

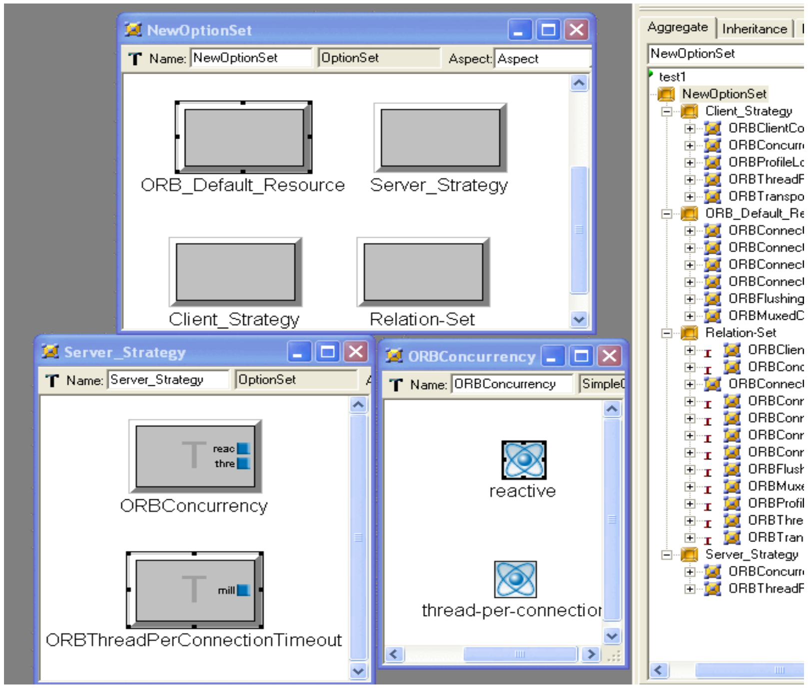
- Develop an ***Options Configuration Modeling Language (OCML)*** w/GME to ensure semantic consistency of option configurations
- OCML is used by
  - **Middleware developers** to design the *configuration model*
  - **Application developers** to configure the middleware for a specific application
- OCML *metamodel* is platform-independent
- OCML *models* are platform-specific

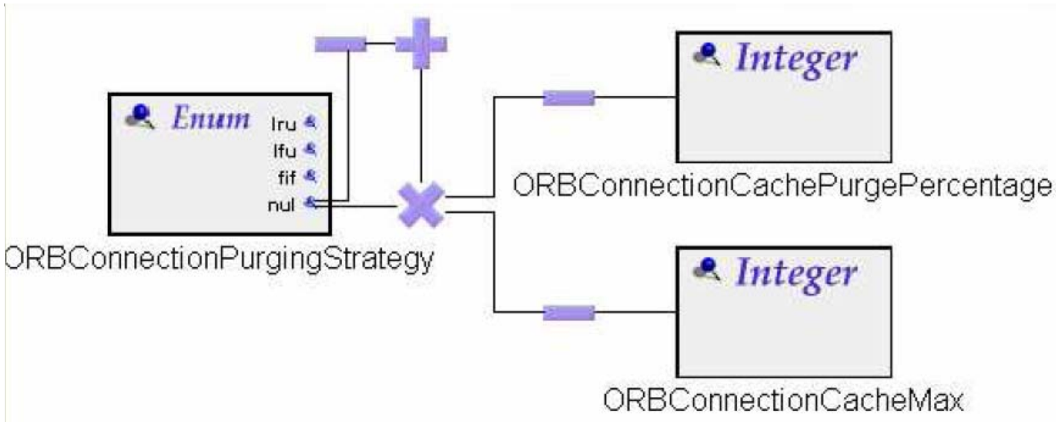


www.cs.wustl.edu/~schmidt/PDF/RTAS-process.pdf

Applying OCML to CIAO+TAO

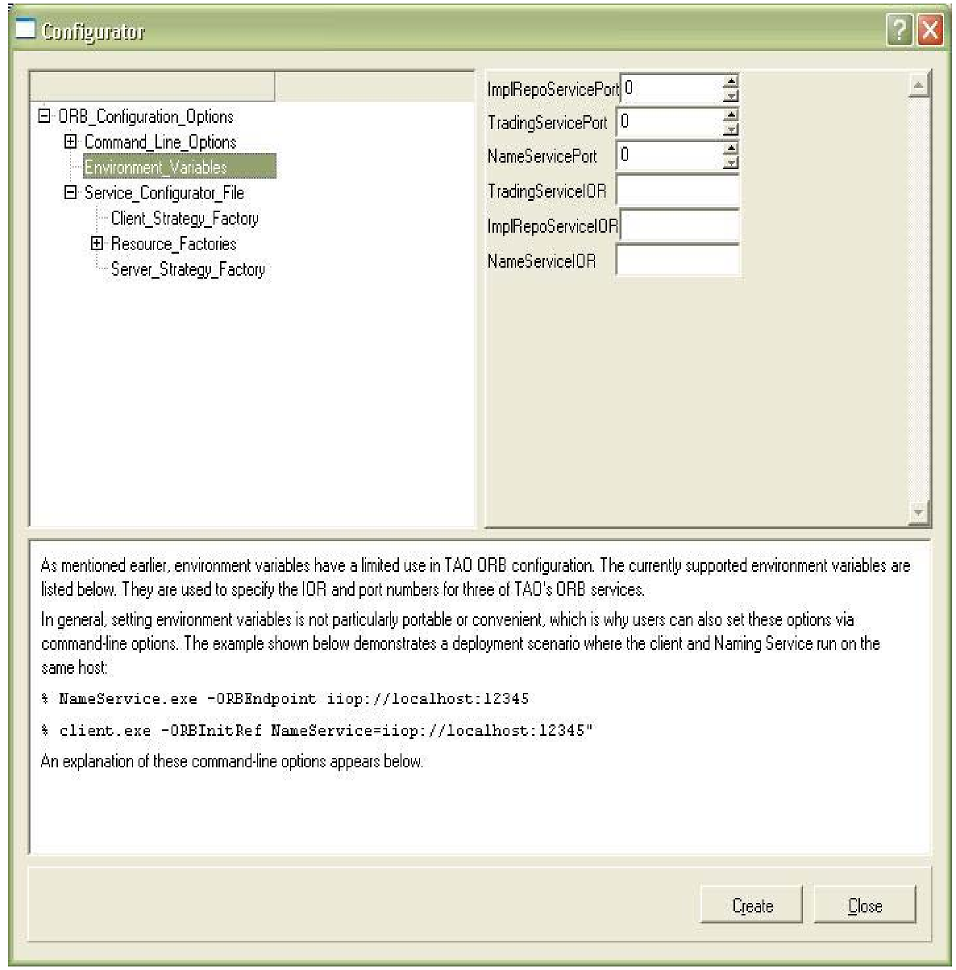
- Middleware developers specify
  - Configuration space
  - Constraints
- OCML generates config model





Applying OCML to CIAO+TAO

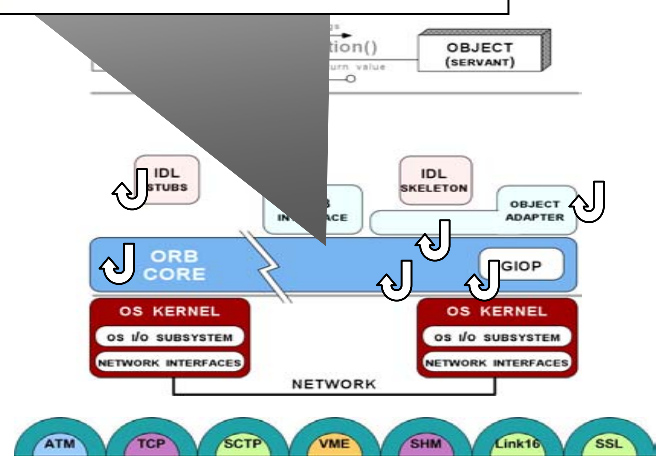
- Middleware developers specify
  - Configuration space
  - Constraints
- OCML generates config model
- Application developers provide a model of desired options & their values, e.g.,
  - Network resources
  - Concurrency & connection management strategies



Applying OCML to CIAO+TAO

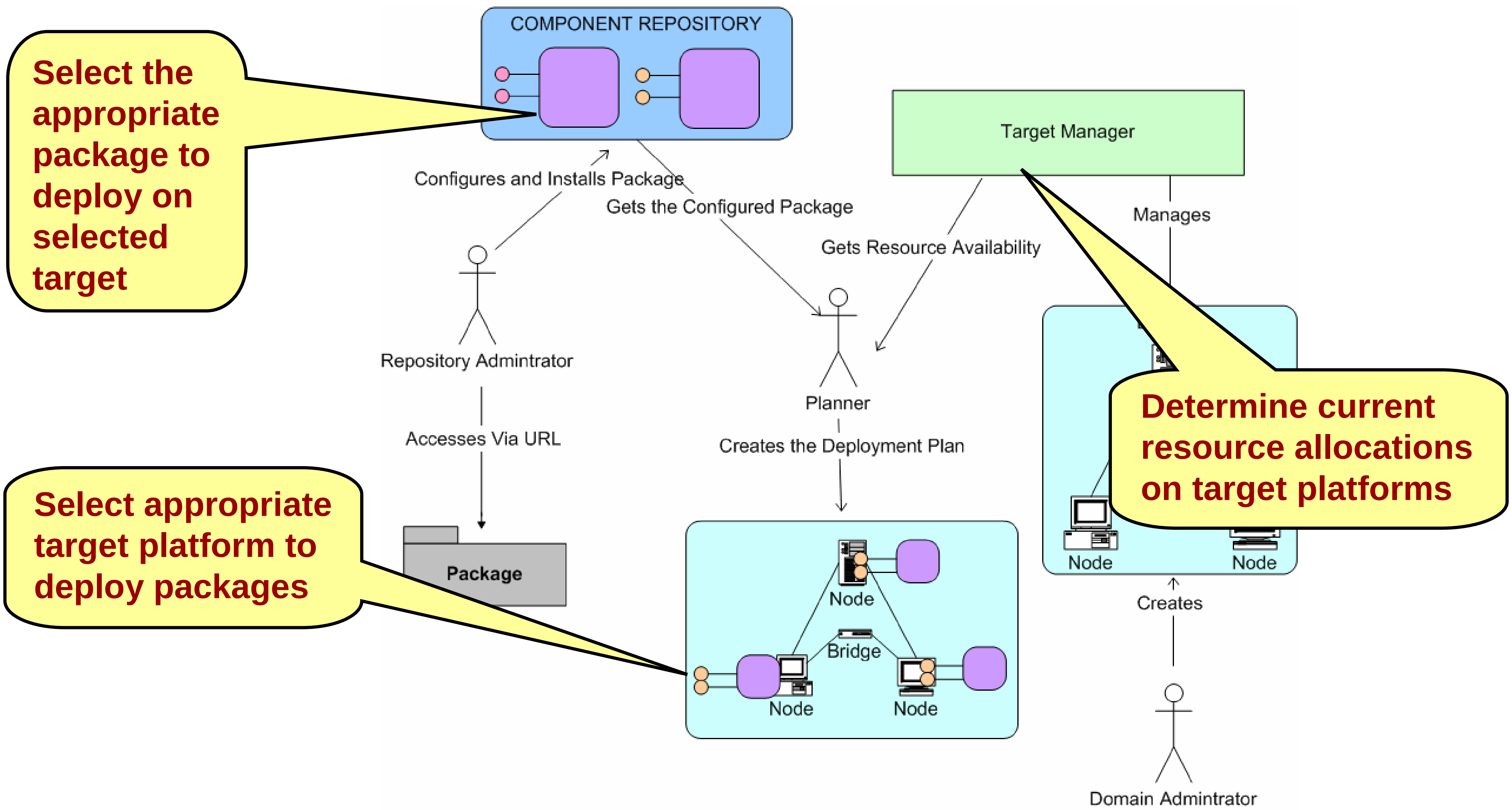
- Middleware developers specify
  - Configuration space
  - Constraints
- OCML generates config model
- Application developers provide a model of desired options & their values, e.g.,
  - Network resources
  - Concurrency & connection management strategies
- OCML constraint checker flags incompatible options & then
  - Synthesizes XML descriptors for middleware configuration
  - Generates documentation for middleware configuration
  - Validates the configurations

```
ests/Latency/Thread_Per_Connection/svc.conf
ACE_Svc_Conf>
 <!--      -->
 <!--   $Id: svc.conf.xml,v 1.1 2002/08/23
 22:23:04 nanbor Exp $   -->
 <!--      -->
 <static id="Advanced_Resource_Factory"
   params="-ORBReactorType select_mt -
   ORBReactorMaskSignals 0 -
   ORBFlushingStrategy blocking" />
 <static id="Client_Strategy_Factory"
   params="-ORBTransportMuxStrategy
   EXCLUSIVE -ORBClientConnectionHandler
   RW" />
 <static id="Server_Strategy_Factory"
   params="-ORBConcurrency thread-per-
   connection" />
/ACE_Svc_Conf>
```



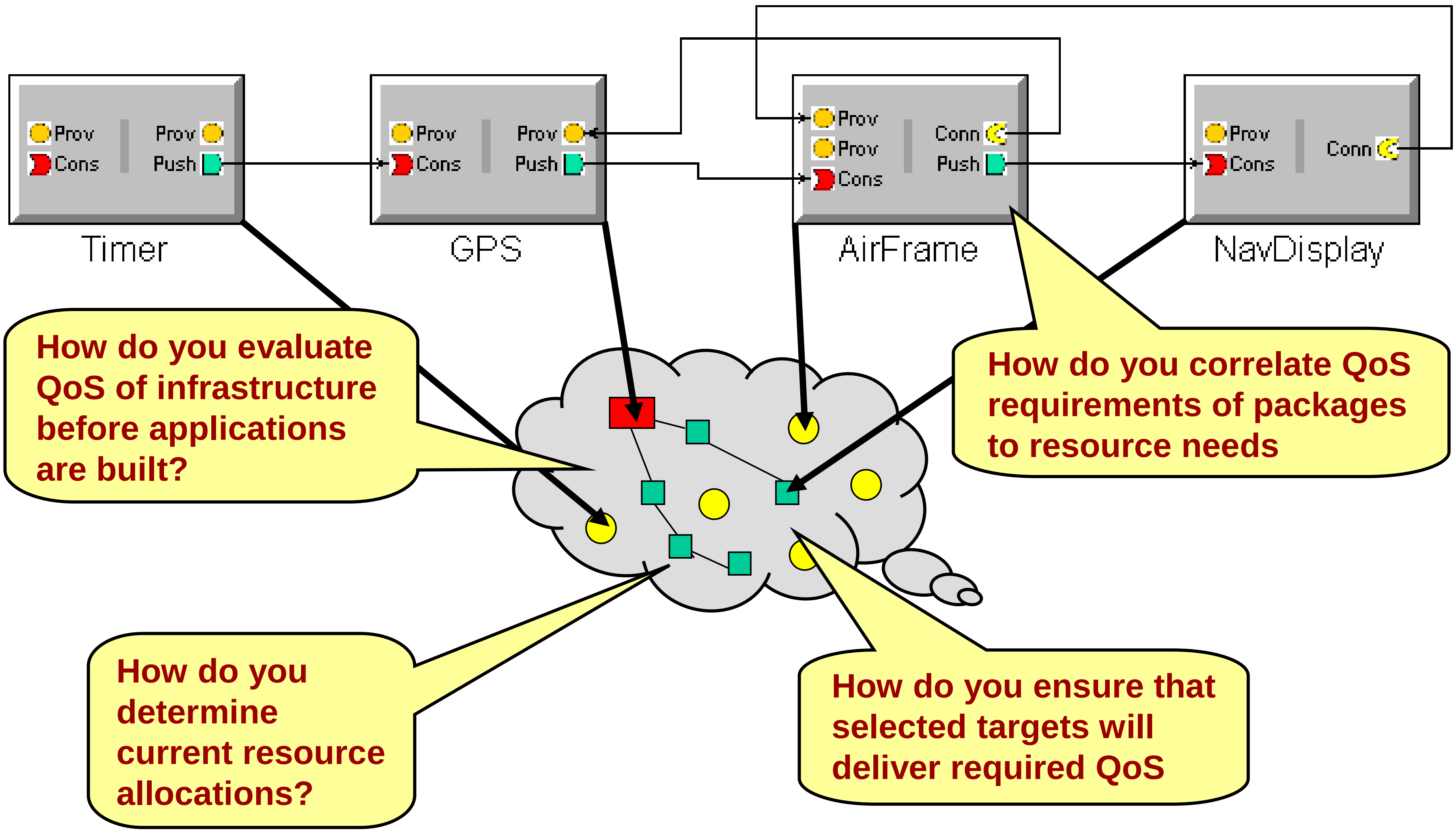
Challenge 3: Planning Aspect

Component integrators must make appropriate deployment decisions, identifying nodes in target environment where packages will be deployed



Planning Aspect Problems

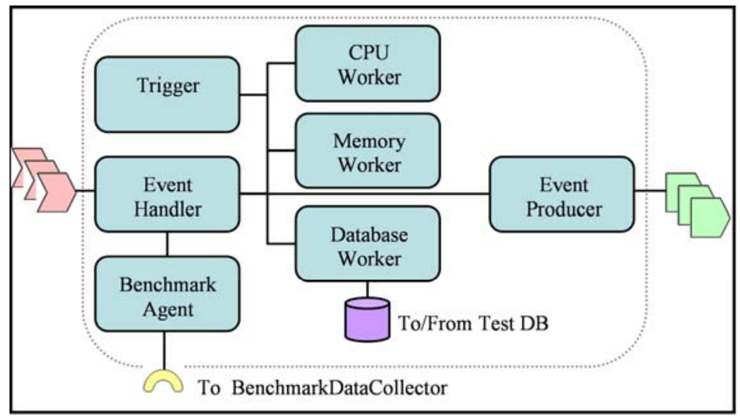
How to ensure deployment plans meet DRE system QoS requirements

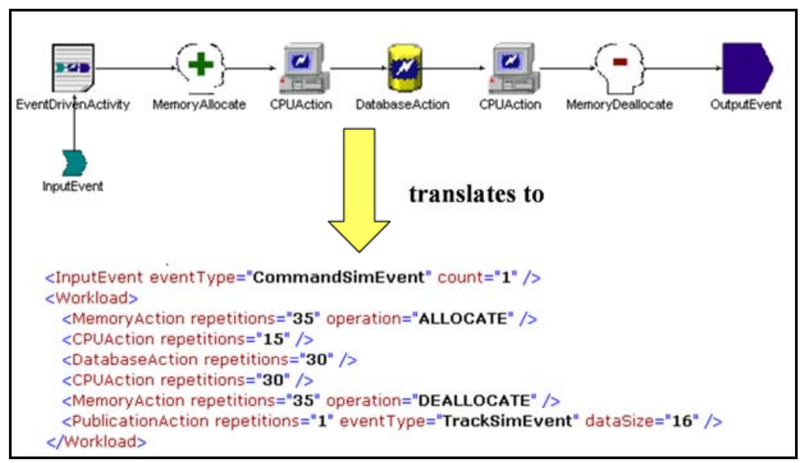


MDD Solution for Planning Aspect

Approach

- Develop ***Component Workload Emulator (CoWorkEr) Utilization Test Suite (CUTS)*** w/GME to allow architects to detect, diagnose, & resolve system QoS problems before system integration phase
  - CoWorkEr is an component assembly of monolithic components responsible for generating respective workload
  - CoWorkEr ports can be connected to define operational strings
  - Workload Modeling Language (WML) is used to define CoWorkEr behavior
  - WML is translated to XML metadata descriptors that configure CoWorkErs

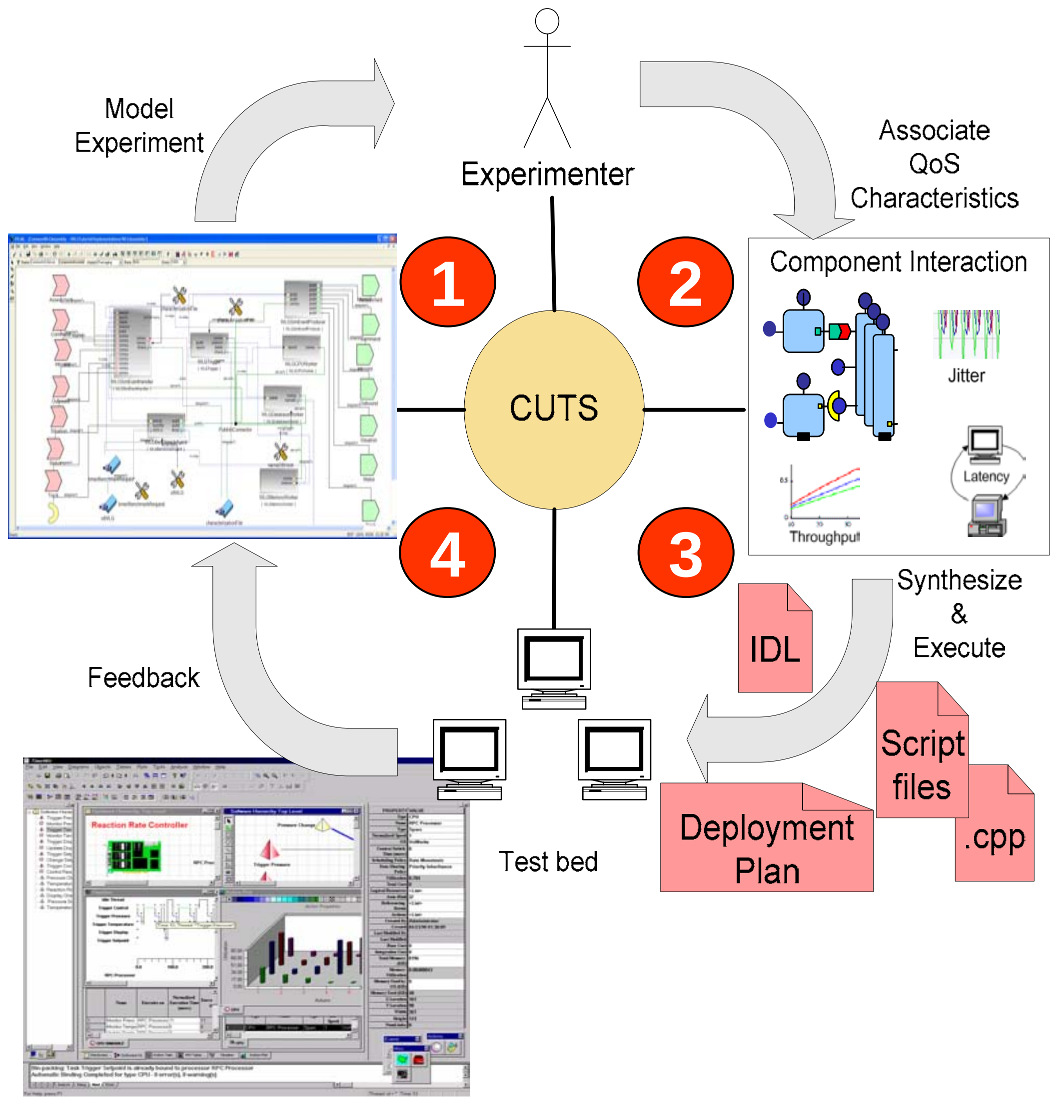




MDD Solution for Planning Aspect

CUTS Workflow for Architects

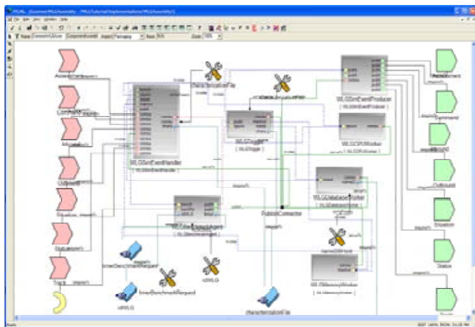
1. Compose scenarios to exercise critical system paths
2. Associate performance properties with scenarios & assign properties to components specific to paths
3. Configure CoWorkers to run experiments, generate deployment plans, & measure performance along critical paths
4. Analyze results to verify if deployment plan & configurations meet performance requirements



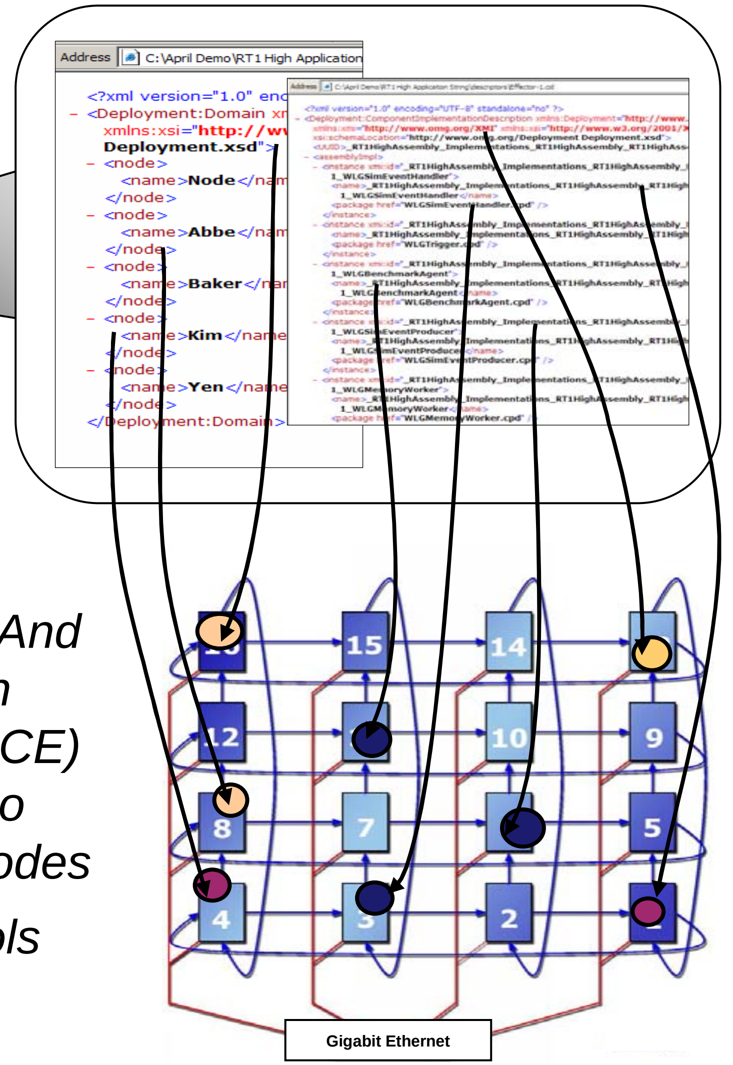
www.cs.wustl.edu/~schmidt/PDF/CUTS.pdf

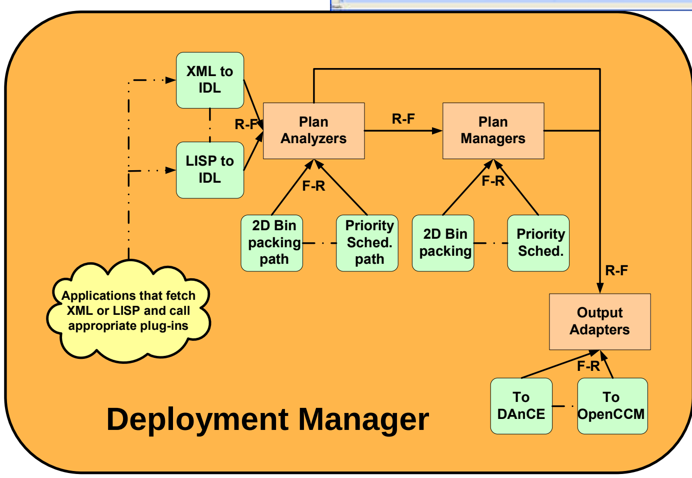
Integrating MDD & Middleware for Planning

CoWorkEr models system components, requirements, & constraints



Deployment Plan



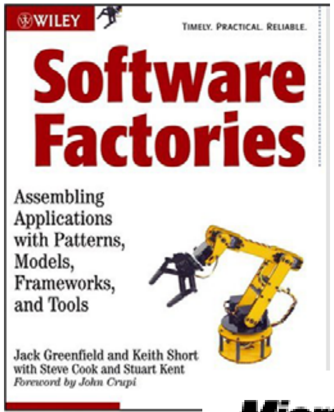


Resource Allocation & Control Engine (RACE) middleware provides deployment planners

- *Deployment And Configuration Engine (DAnCE) maps plans to computing nodes*
- *RACE controls reallocations*

www.cs.wustl.edu/~schmidt/PDF/DAnCE.pdf

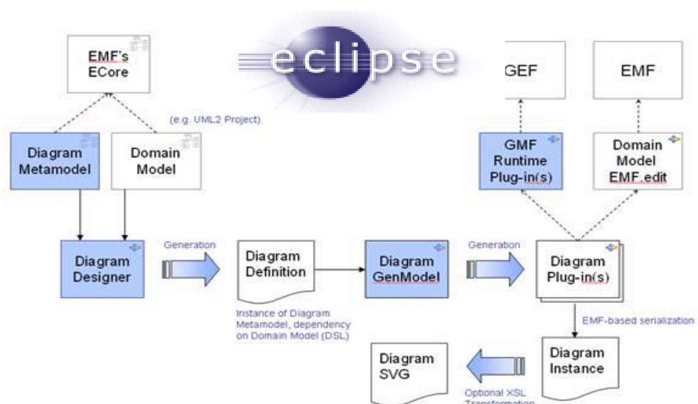
Commercial Related Work



Microsoft

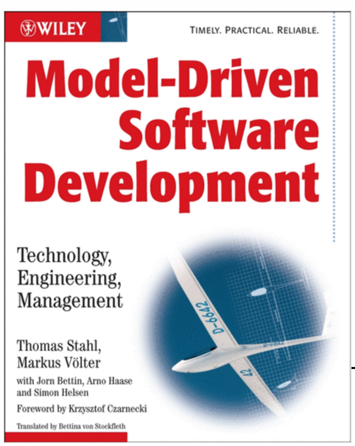
- Software Factories go beyond "models as documentation" by
  - Using highly-tuned DSL & XML as source artifacts &
  - Capturing life cycle metadata to support high-fidelity model transformation, code generation & other forms of automation

www.softwarefactories.com



- The Graphical Modeling Framework (GMF) forms a generative bridge between EMF & GEF, which linkes diagram definitions to domain models as input to generation of visual editors
- GMF provides this framework, in addition to tools for select domain models that illustrate its capabilities

www.eclipse.org/gmf/

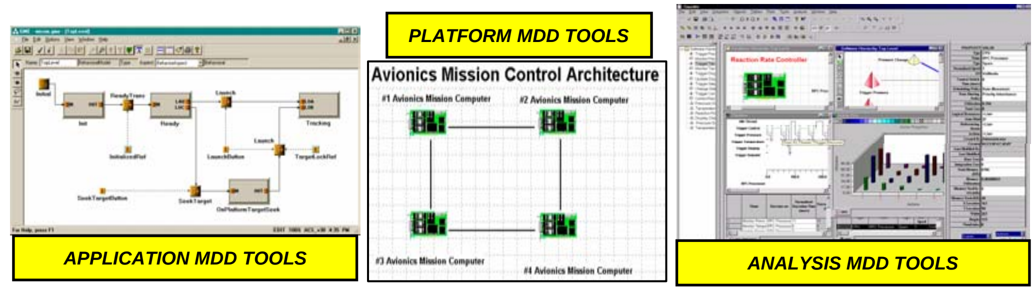


- openArchitectureWare (oAW) is a modular MDA/MDE generator framework implemented in Java
- It supports parsing of arbitrary models & a language family to check & transform models, as well as generate code based on them

www.openarchitectureware.org

Concluding Remarks

- To realize the promise of model-driven technologies, we need to augment model-driven methodologies with a solid (ideally standard) tool infrastructure
- Model-driven tools need to coexist with & enhance existing middleware platform technologies
- We need to validate model-driven technologies on (increasingly) large-scale, real-world systems



Although hard problems with model-driven technologies remain, we're reaching critical mass after decades of R&D & commercial progress

- Open-source CoSMIC MDD tools use Generic Modeling Environment (GME)
  - CoSMIC is available from www.dre.vanderbilt.edu/cosmic
  - GME is available from www.isis.vanderbilt.edu/Projects/gme/default.htm