Meeting the Challenges of Ultra-Large-Scale Distributed Real-time & Embedded Systems with QoS-enabled Middleware & Model-Driven Engineering

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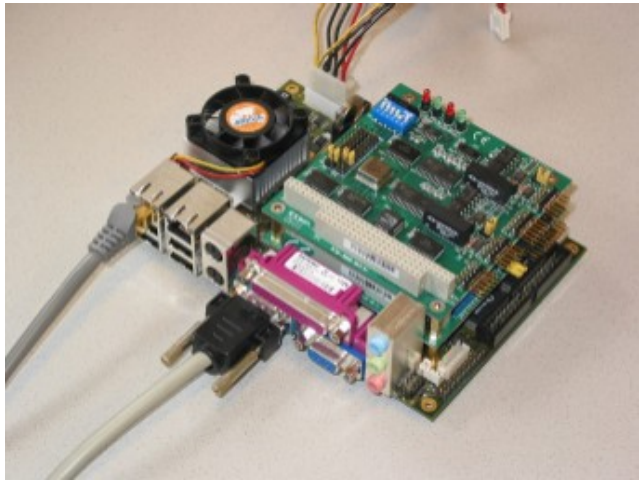
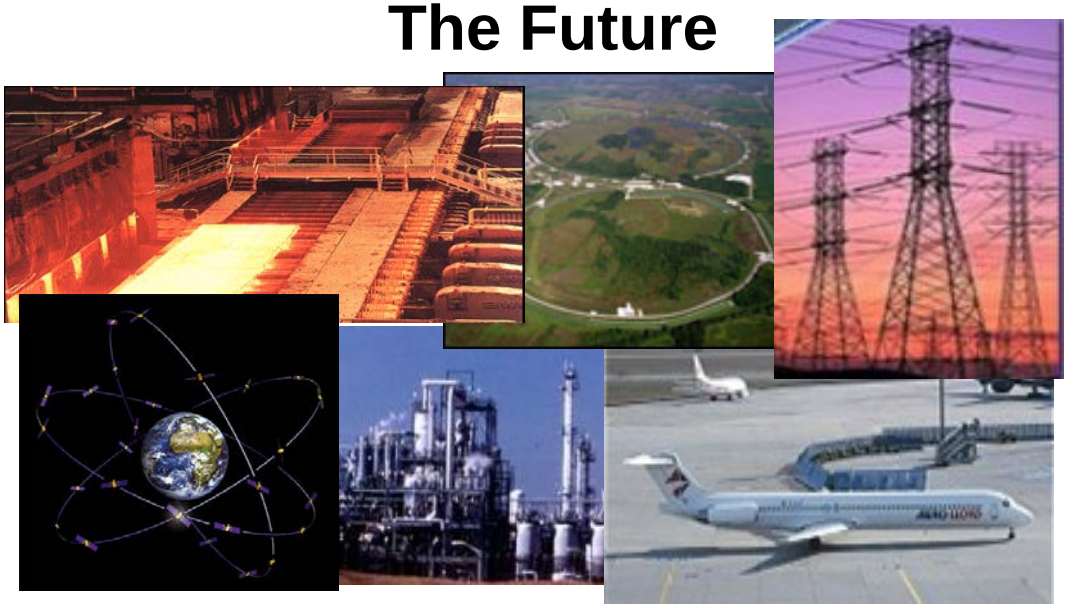
Evolution in Distributed Real-time & Embedded (DRE) Systems

The Past



The Future



Stand-alone real-time & embedded systems

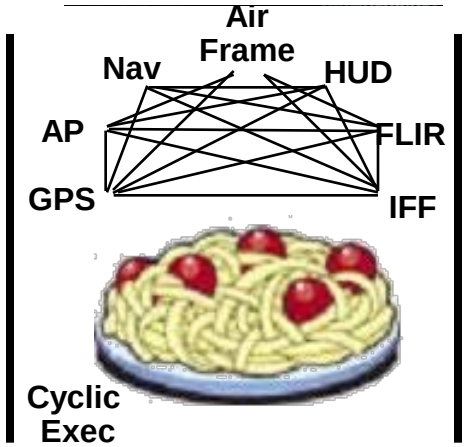
- Stringent quality of service (QoS) demands
  - e.g., latency, jitter, footprint
- Resource constrained

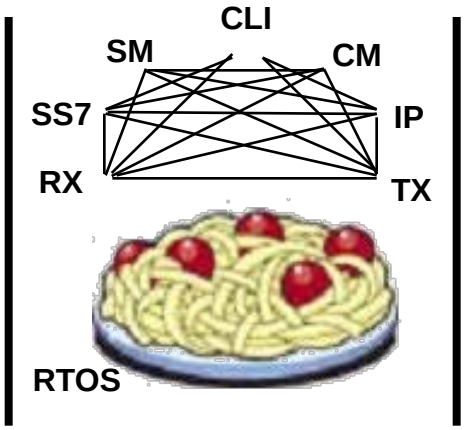
Enterprise distributed real-time & embedded (DRE) systems

- Network-centric "systems of systems"
- Stringent simultaneous QoS demands
  - e.g., dependability, security, scalability, etc.
- Dynamic context

This talk focuses on technologies for enhancing DRE system QoS, productivity, & quality

Evolution of DRE Systems Development





Technology Problems

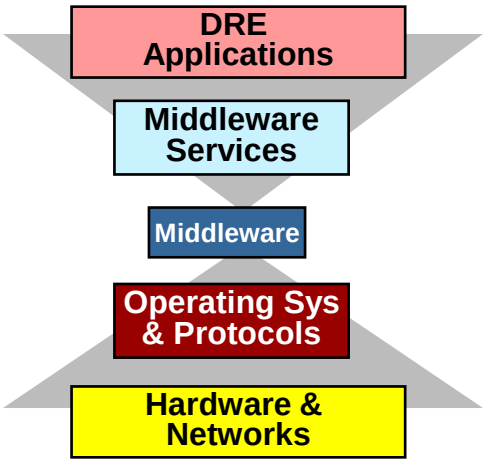
- Legacy DRE systems often tend to be:
  - Stovepiped
  - Proprietary
  - Brittle & non-adaptive
  - Expensive
  - Vulnerable

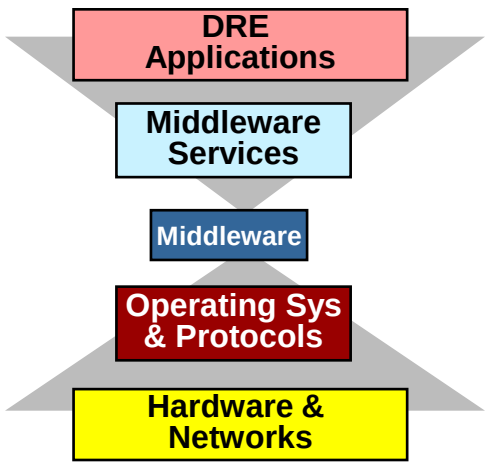
Mission-critical DRE systems have historically been built directly atop hardware

- 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





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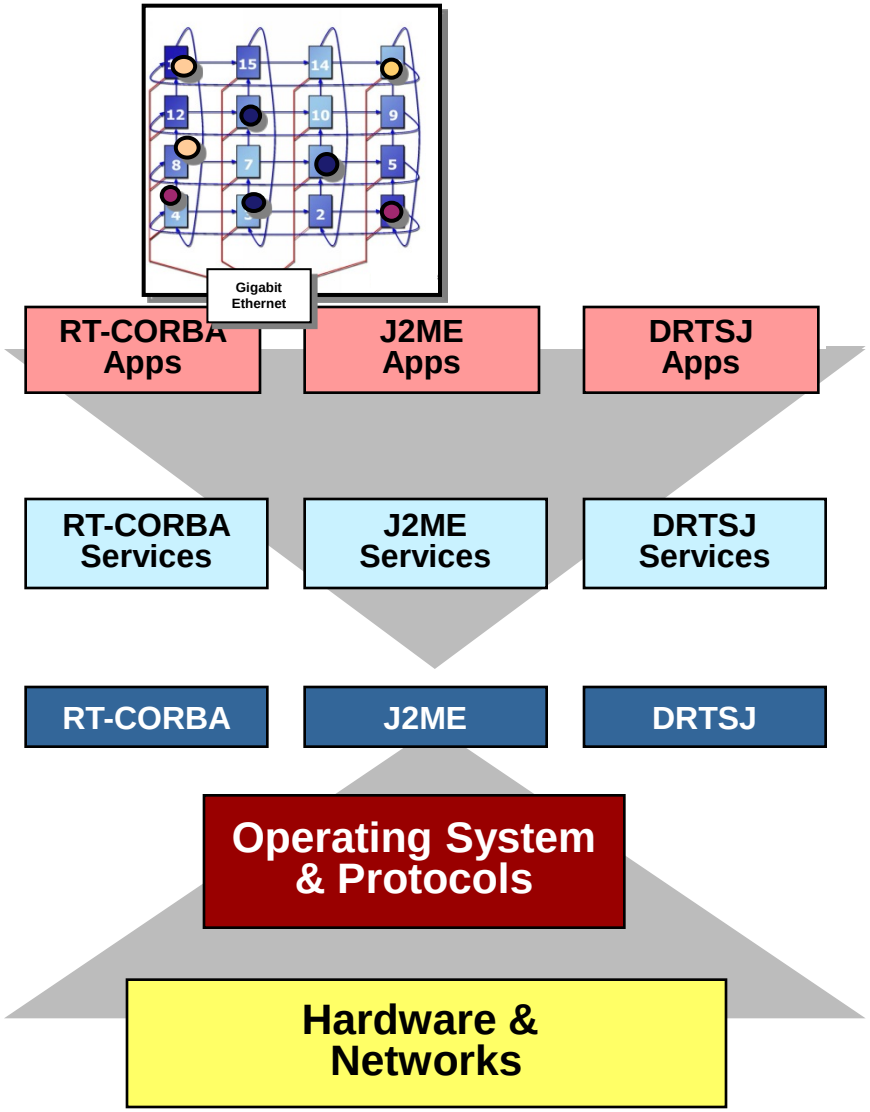
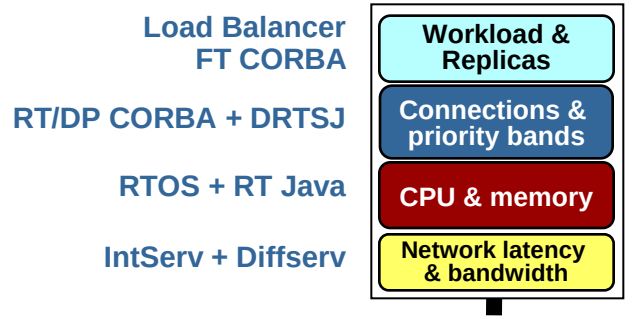
- Middleware has effectively factored out many reusable services from traditional DRE application responsibility
  - Essential for ***product-line architectures***
- Middleware is no longer the primary DRE system performance bottleneck

DRE Systems: The Challenges Ahead



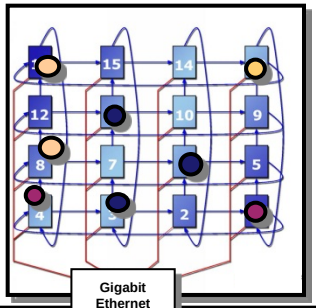
- Limit to how much application functionality can be refactored into reusable COTS middleware
- Middleware itself has become very hard to use & provision statically & dynamically

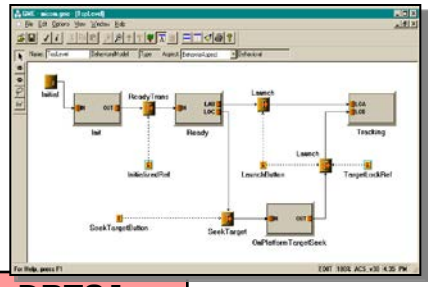


- Component-based DRE systems are also very hard to deploy & configure
- There are many middleware platform technologies to choose from

Middleware alone cannot solve large-scale DRE system challenges!

Promising Solution: *Model-based Software Development*





RT-CORBA Apps | J2ME Apps | DRTSJ Apps

RT-CORBA | J2ME Services | DRTSJ Services

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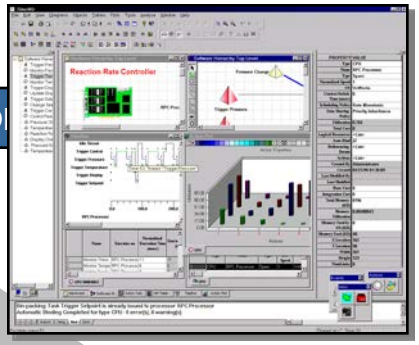
J2ME | D



Operating System & Protocols

Hardware & Networks

- Develop, validate, & standardize generative software technologies that:
  1. ***Model***
  2. ***Analyze***
  3. ***Synthesize &***
  4. ***Provision***

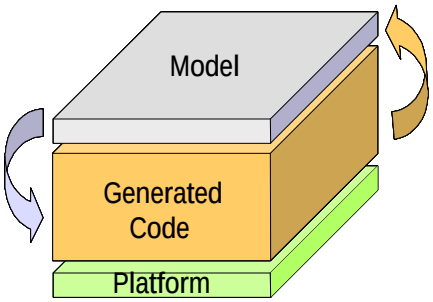
  multiple layers of middleware & application components that require simultaneous control of multiple QoS properties end-to-end
- Partial specialization is essential for inter-/intra-layer optimization & advanced product-line architectures

Goal is to ***enhance developer productivity & software quality*** by providing ***higher-level languages & tools*** for middleware/application developers & users

Technology Evolution (1/4)

Level of Abstraction

Programming Languages & Platforms



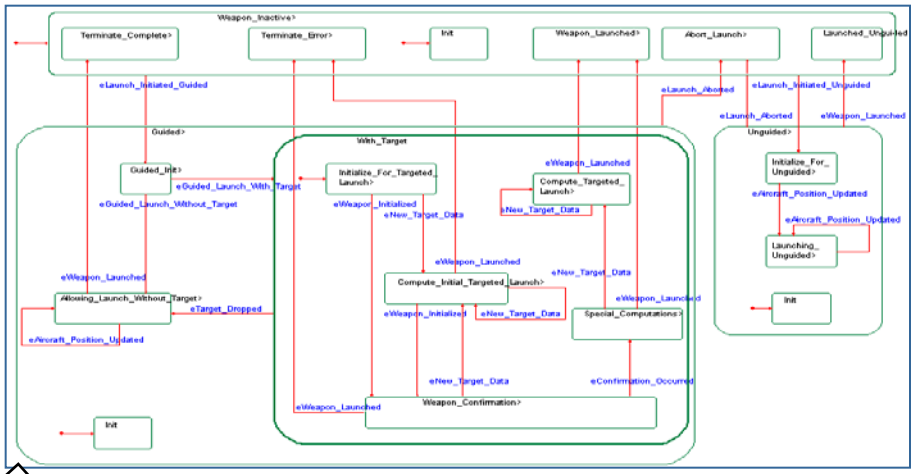
Translation
Translation
Translation

Large Semantic Gap

Operating Systems
Hardware

C/Fortran
Assembly
Machine code

Model-Driven Engineering (MDE)



- State chart
- Data & process flow
- Petri Nets

Technology Evolution (2/4)

Level of Abstraction

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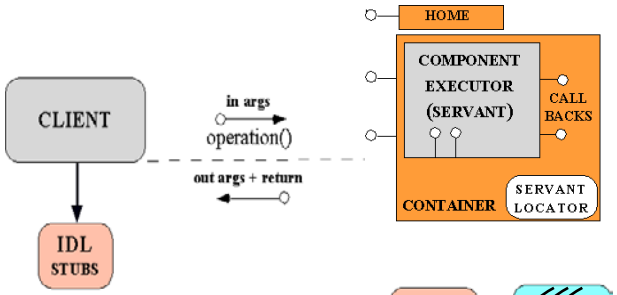
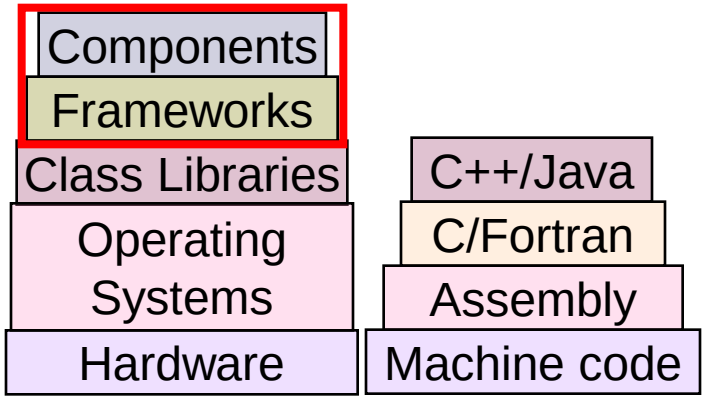
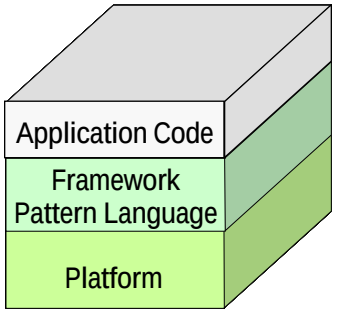




- Newer 3rd-generation languages & platforms have raised abstraction level significantly
  - "Horizontal" platform reuse alleviates the need to redevelop common services



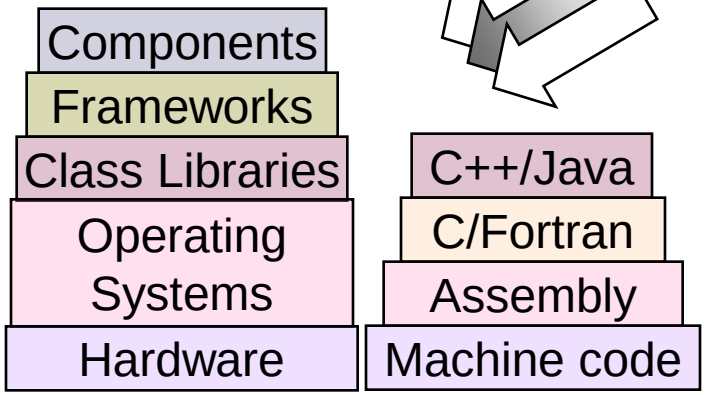
- There are two problems, however:
  - Platform complexity evolved faster than 3rd-generation languages
  - Much application/platform code still (unnecessarily) written manually

Technology Evolution (3/4)

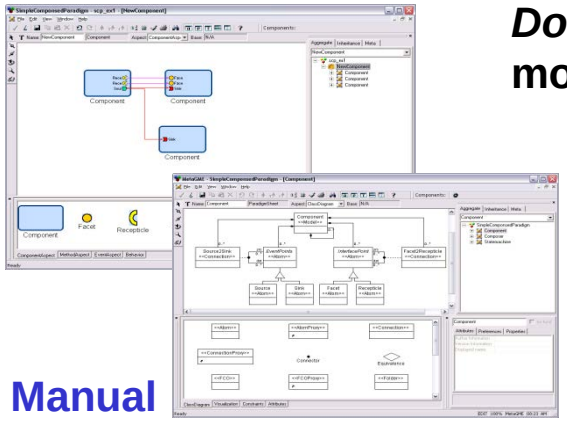
Level of Abstraction

Programming Languages & Platforms

Saturation!!!!



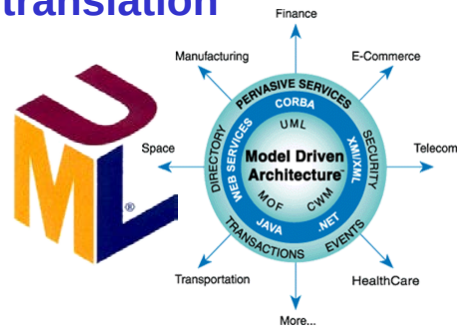
Model-Driven Engineering (MDE)



Domain-specific **modeling languages**

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

Manual translation



Domain-independent modeling languages

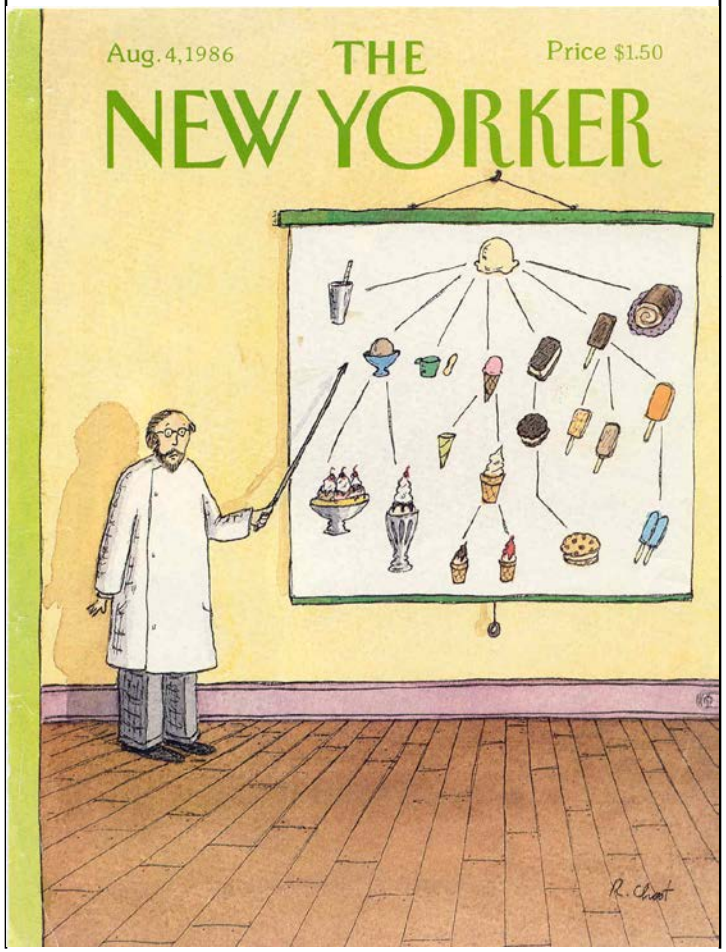
- State Charts
- Interaction Diagrams
- Activity Diagrams

Semi-automated

Technology Evolution (3/4)

Level of Abstraction

Programming Languages & Platforms



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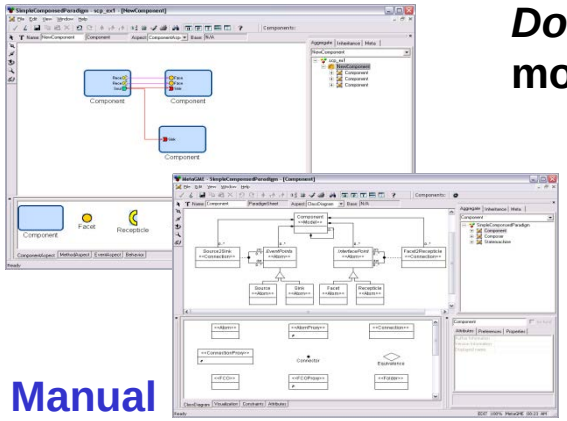

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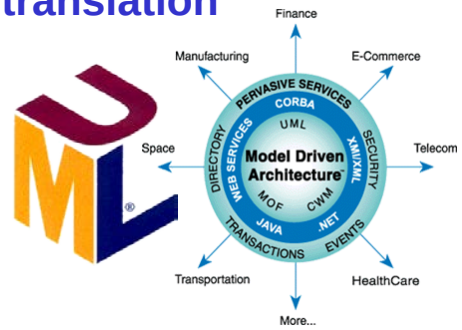

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  - mic.omg.org

Technology Evolution (3/4)

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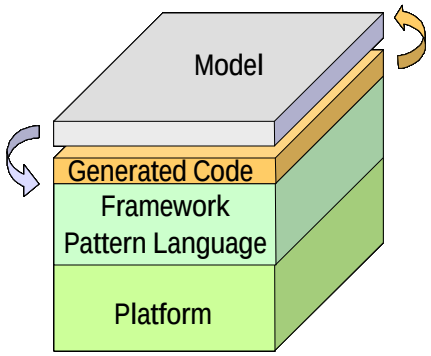

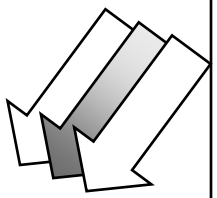

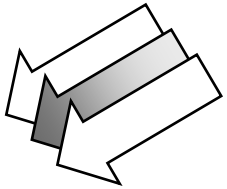

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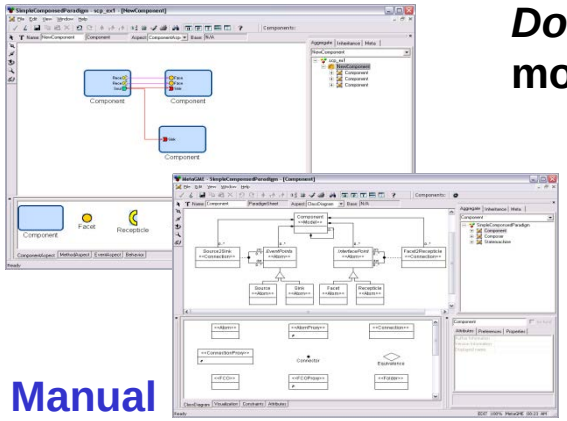

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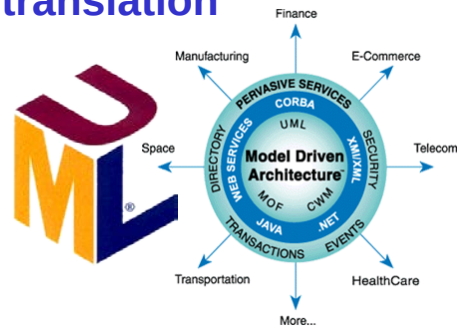

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Technology Evolution (4/4)

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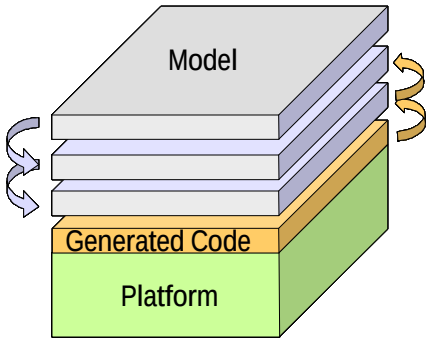
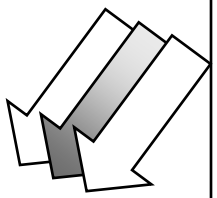
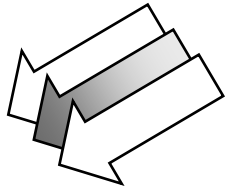
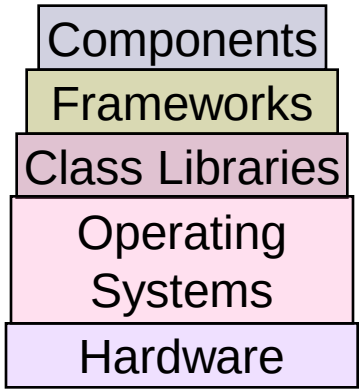
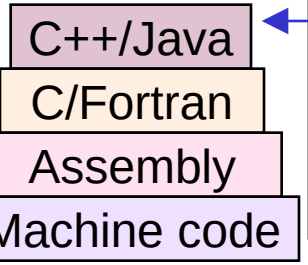


Needs Automation









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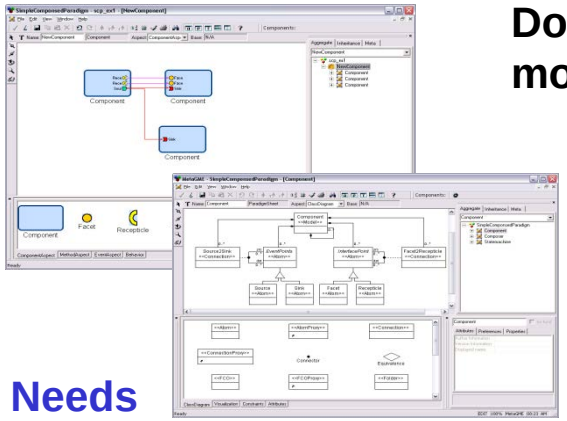

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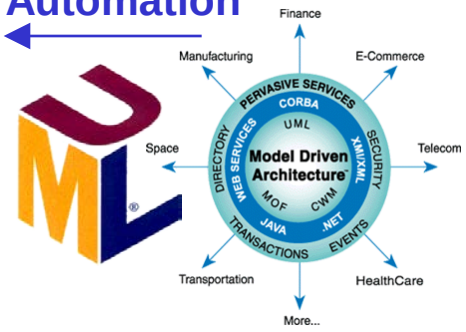

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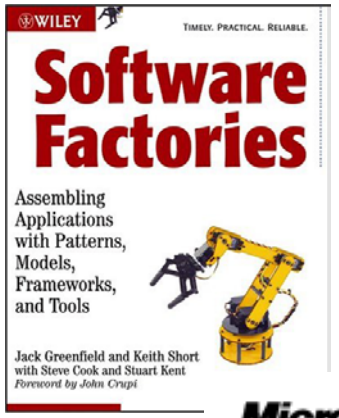
Needs Automation

Research is needed to automate DSMLs & model translators

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

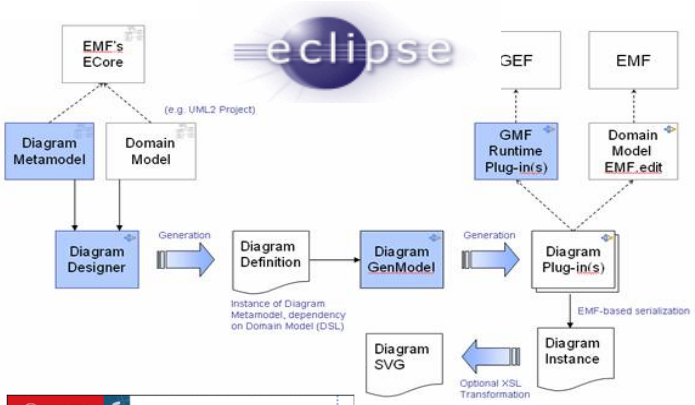
Crossing the Chasm



Microsoft

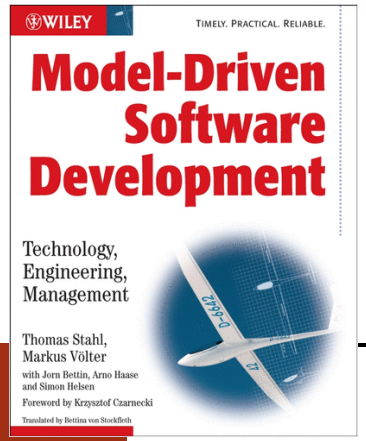
- Software Factories go beyond “models as documentation” by
  - Using highly-tuned DSL & XML as source artifacts &
  - Capturing life cycle metadata to support high-fidelity model transformation, code generation & other forms of automation

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

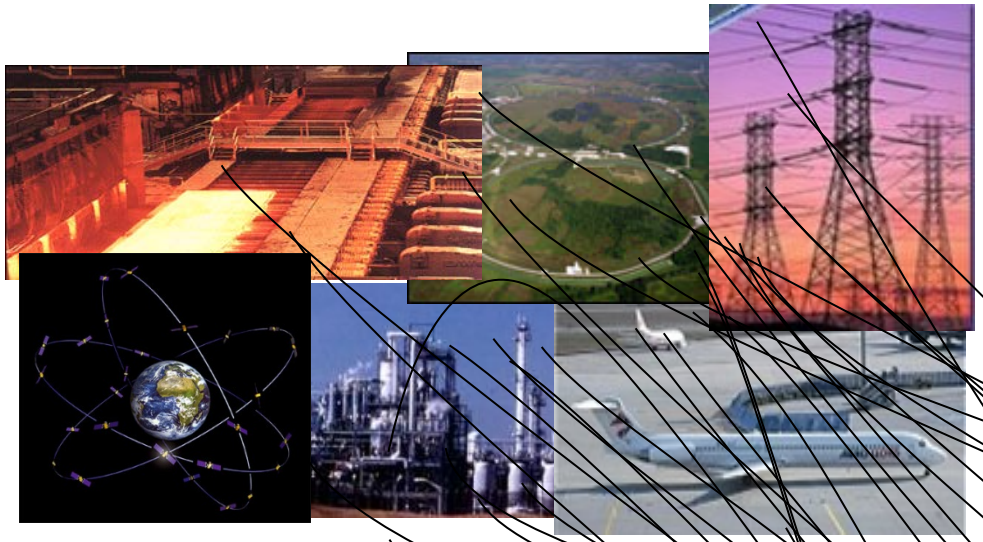
www.eclipse.org/gmf/



- 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

New Challenges: Ultra-Large-Scale (ULS) Systems



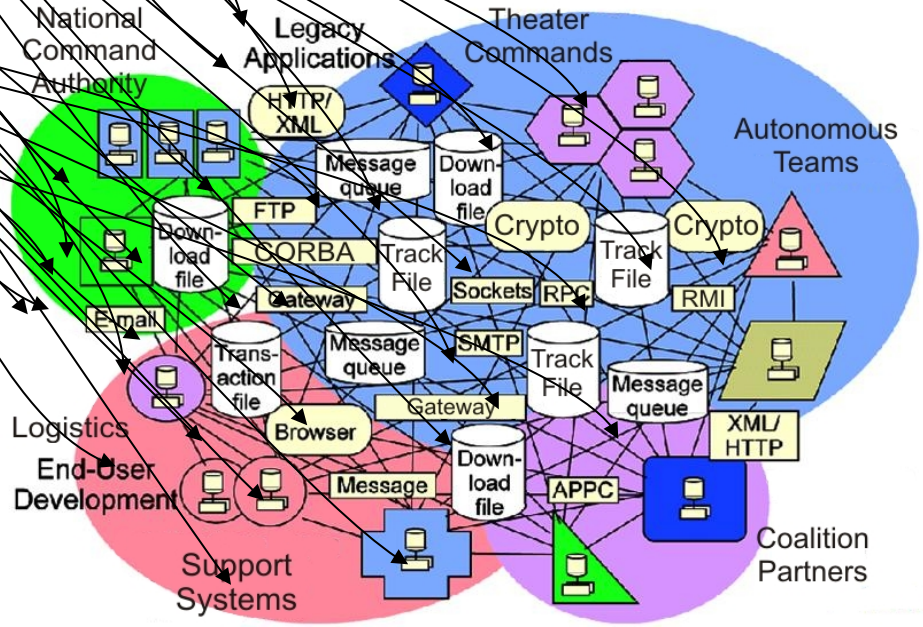
Key ULS ***problem space*** challenges

- Highly dynamic & distributed development & operational environments
- Stringent simultaneous quality of service (QoS) demands
- Very diverse & complex network-centric application domains

Key ULS ***solution space*** challenges

- Enormous accidental & inherent complexities
- Continuous evolution & change
- Highly heterogeneous platform, language, & tool environments

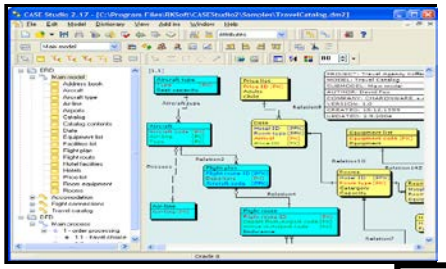
Mapping *problem space requirements* to *solution space artifacts* is very hard

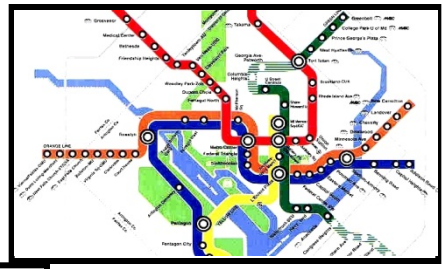


Key R&D Challenges for ULS Systems

Developers & users of ULS systems face challenges in multiple dimensions

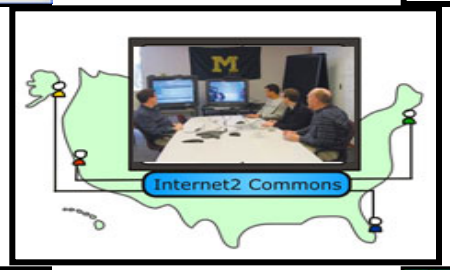
Logical View



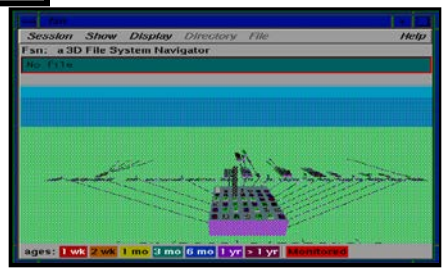


Process View

Use Case View



Physical View



Development View

Of course, developers of today's large-scale DRE systems also face these challenges, but they can often "brute force" solutions…

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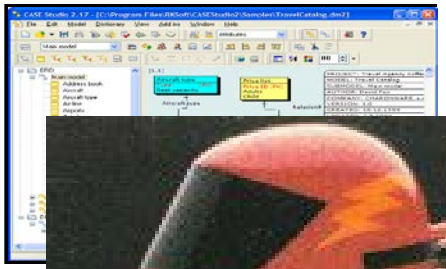
Logical View



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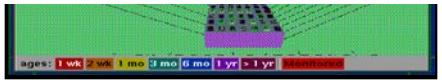
Physical View



Development View

Solving these challenges requires much more than simply retrofitting our current tools, platforms, & processes!

Key R&D Challenges for ULS Systems

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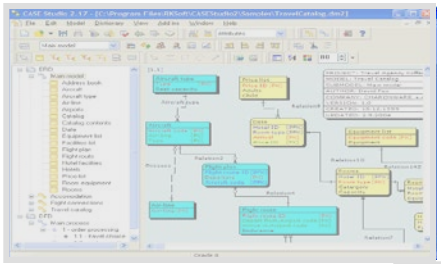
Logical View



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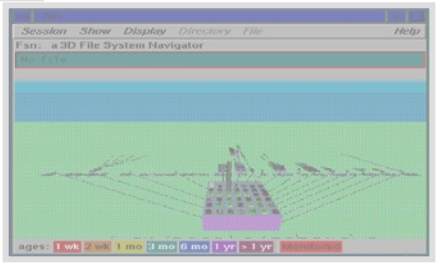
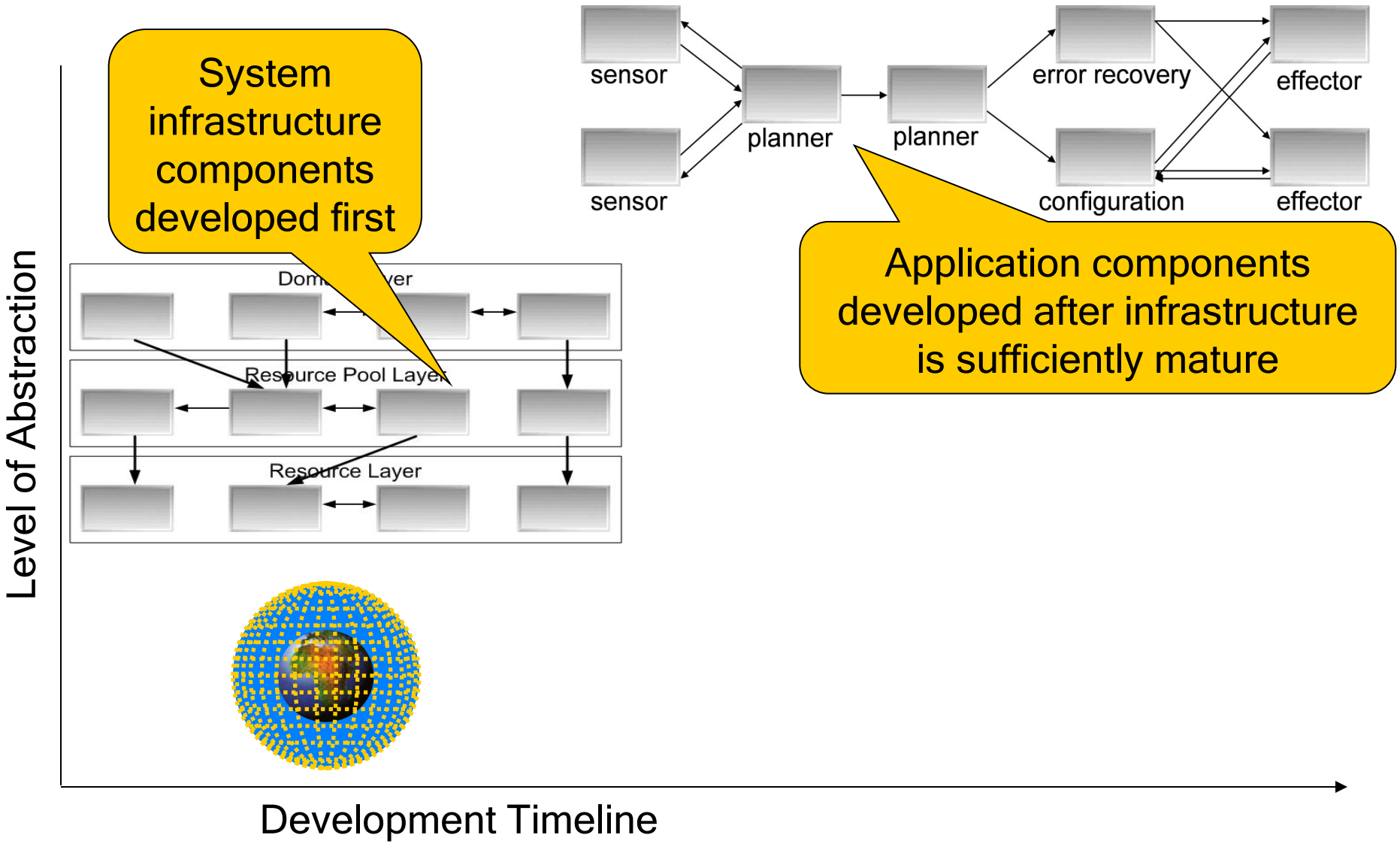
Use Case View

Physical View



Development View

Serialized Phasing is Common in ULS Systems



Serialized Phasing is Common in ULS Systems

System integration & testing is performed after application development is finished

sensor
sensor
planner
planner
error recovery
configuration
effector
effector

Domain
Resource P er
Resource er

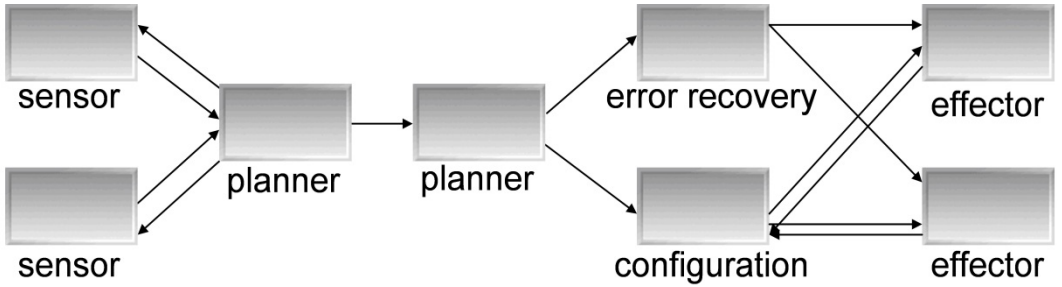
Integration Surprises!!!

Level of Abstraction

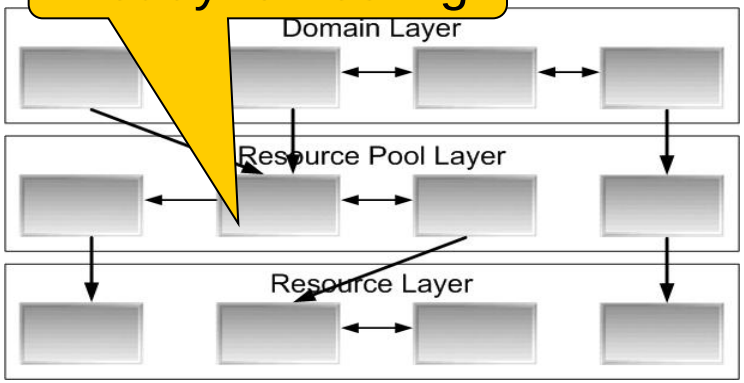
Development Timeline

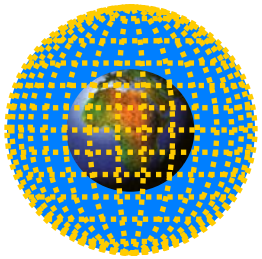
Complexities of Serialized Phasing

Still in development



Ready for testing





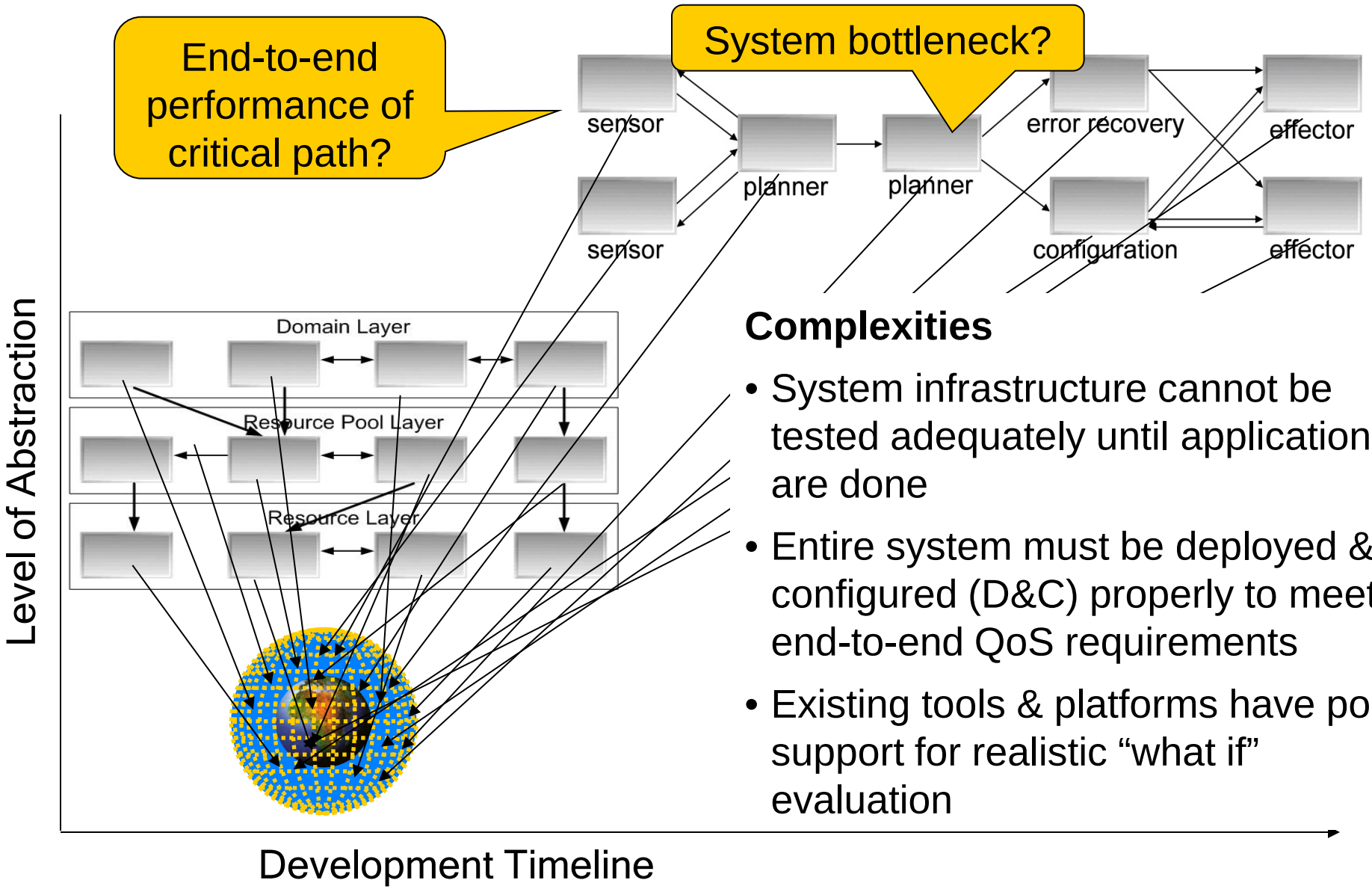
Level of Abstraction

Development Timeline

Complexities

- System infrastructure cannot be tested adequately until applications are done

Complexities of Serialized Phasing

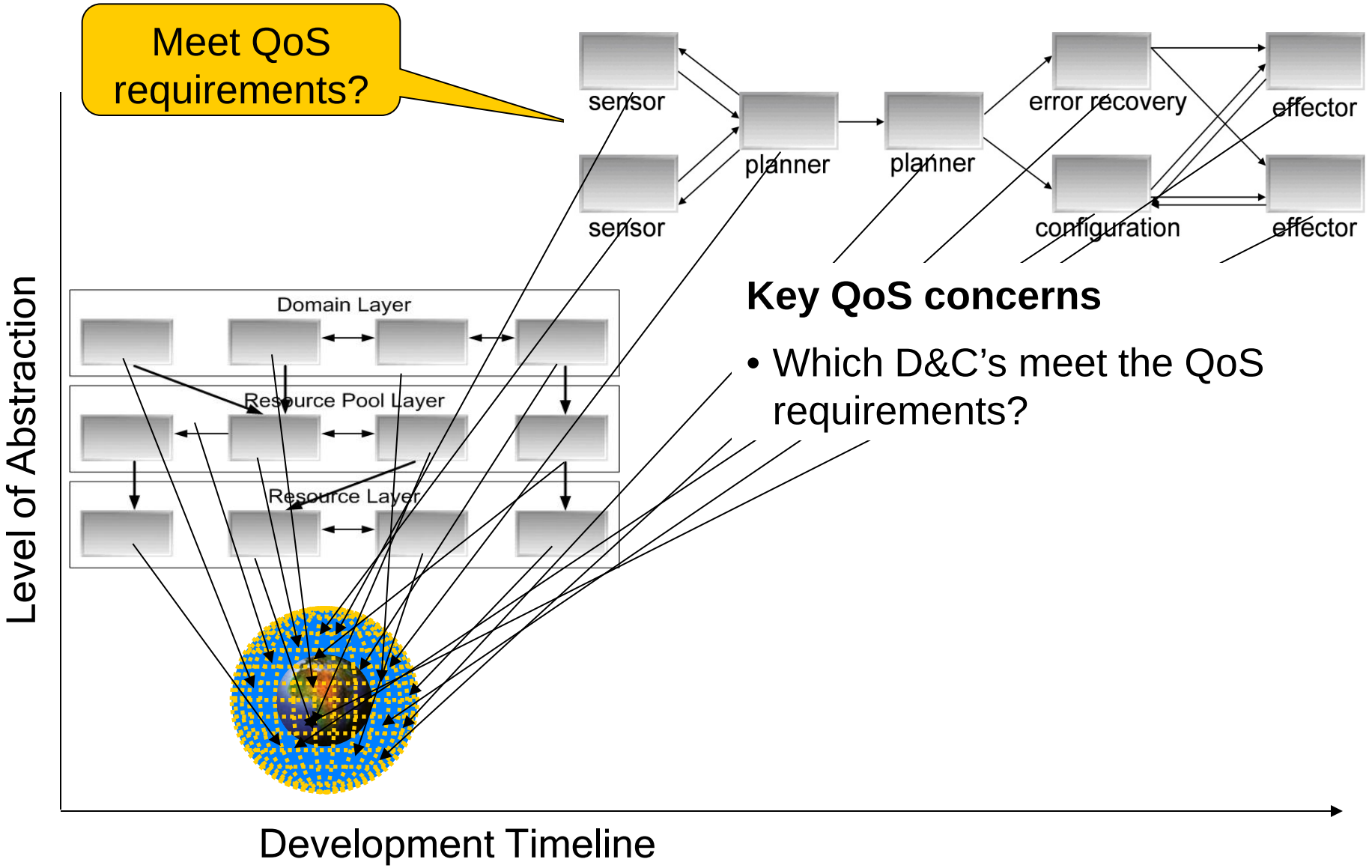


Complexities

- System infrastructure cannot be tested adequately until applications are done
- Entire system must be deployed & configured (D&C) properly to meet end-to-end QoS requirements
- Existing tools & platforms have poor support for realistic “what if” evaluation

QoS needs of components in ULS systems often unknown until late in lifecycle

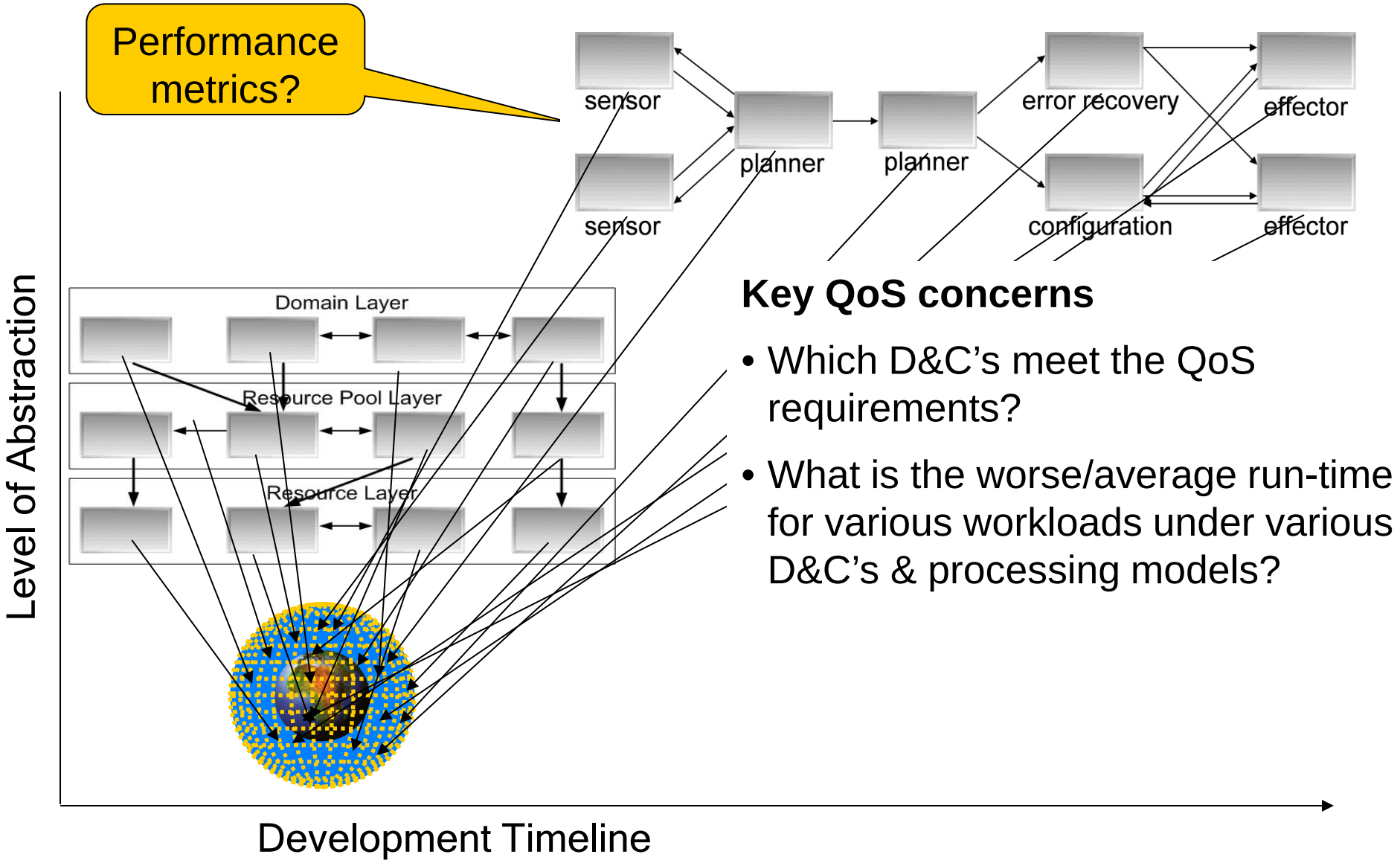
Unresolved QoS Concerns with Serialized Phasing



Key QoS concerns

- Which D&C's meet the QoS requirements?

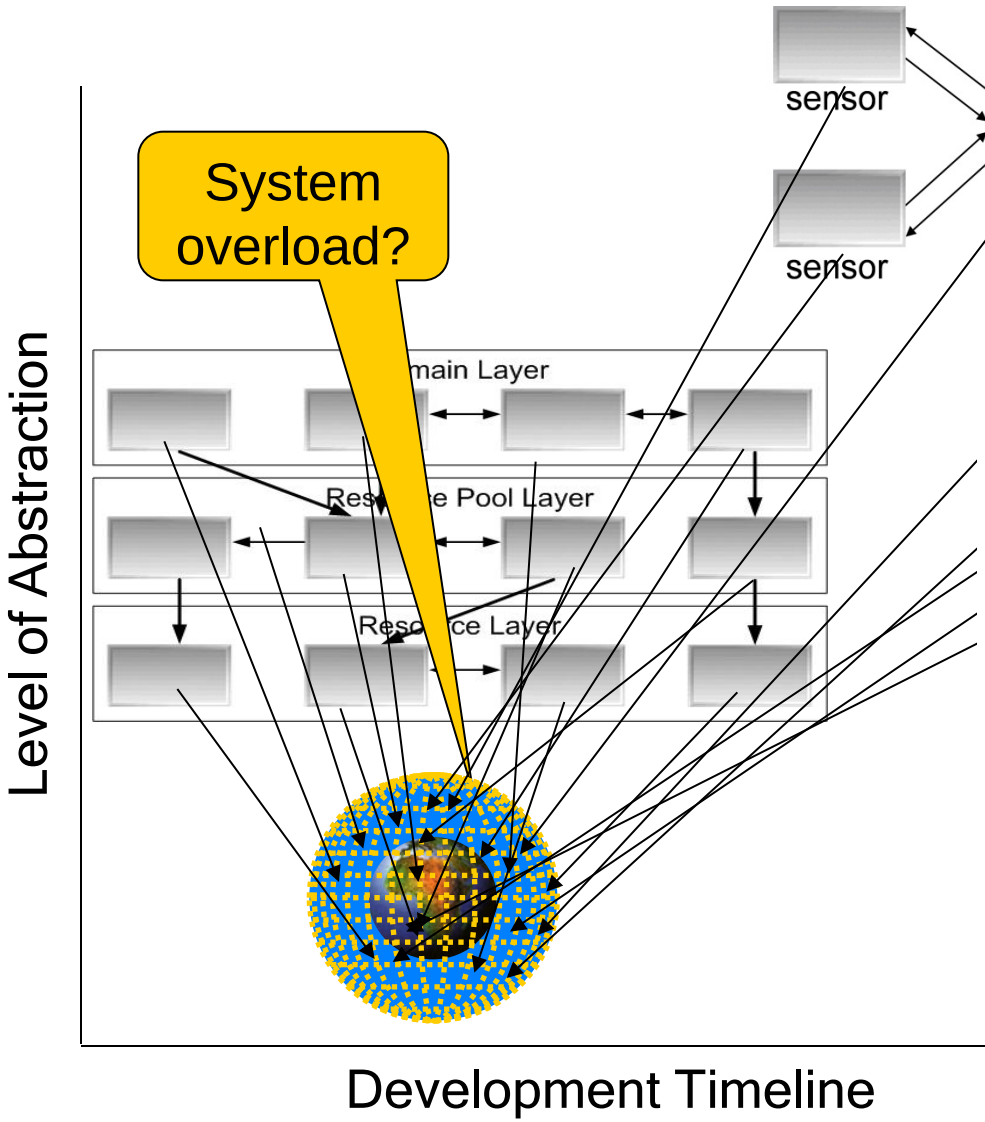
Unresolved QoS Concerns with Serialized Phasing



Key QoS concerns

- Which D&C's meet the QoS requirements?
- What is the worse/average run-time for various workloads under various D&C's & processing models?

Unresolved QoS Concerns with Serialized Phasing

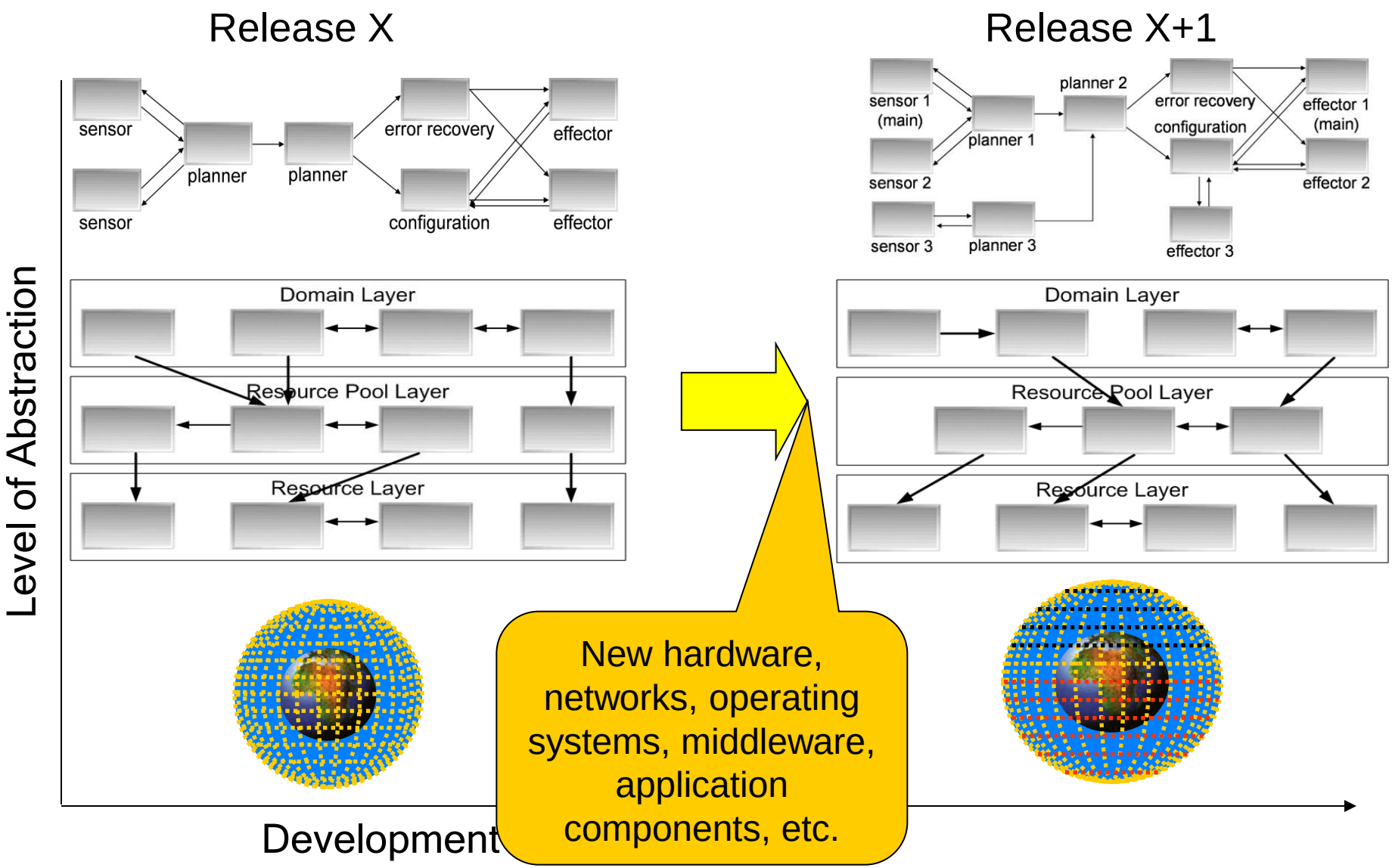


Key QoS concerns

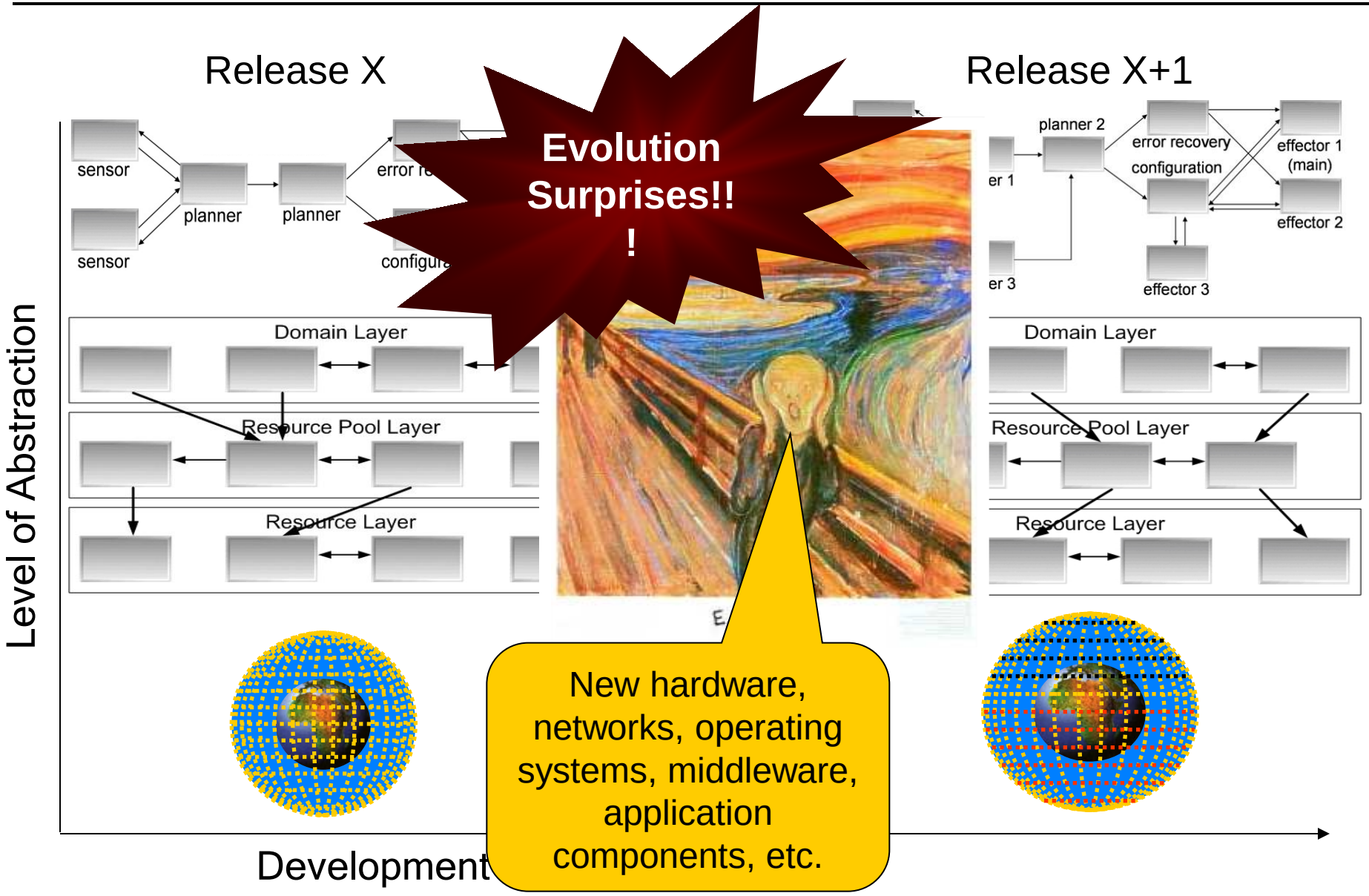
- Which D&C's meet the QoS requirements?
- What is the worse/average run-time for various workloads under various D&C's & processing models?
- How much workload can the system handle until its end-to-end QoS requirements are compromised?

It can take a *long* time (years) to address QoS concerns with serialized phasing

Related ULS System Development Problems



Related ULS System Development Problems



Promising Approach for ULS System Challenges:

System Execution Modeling (SEM) Tools

Tools to express & validate design rules

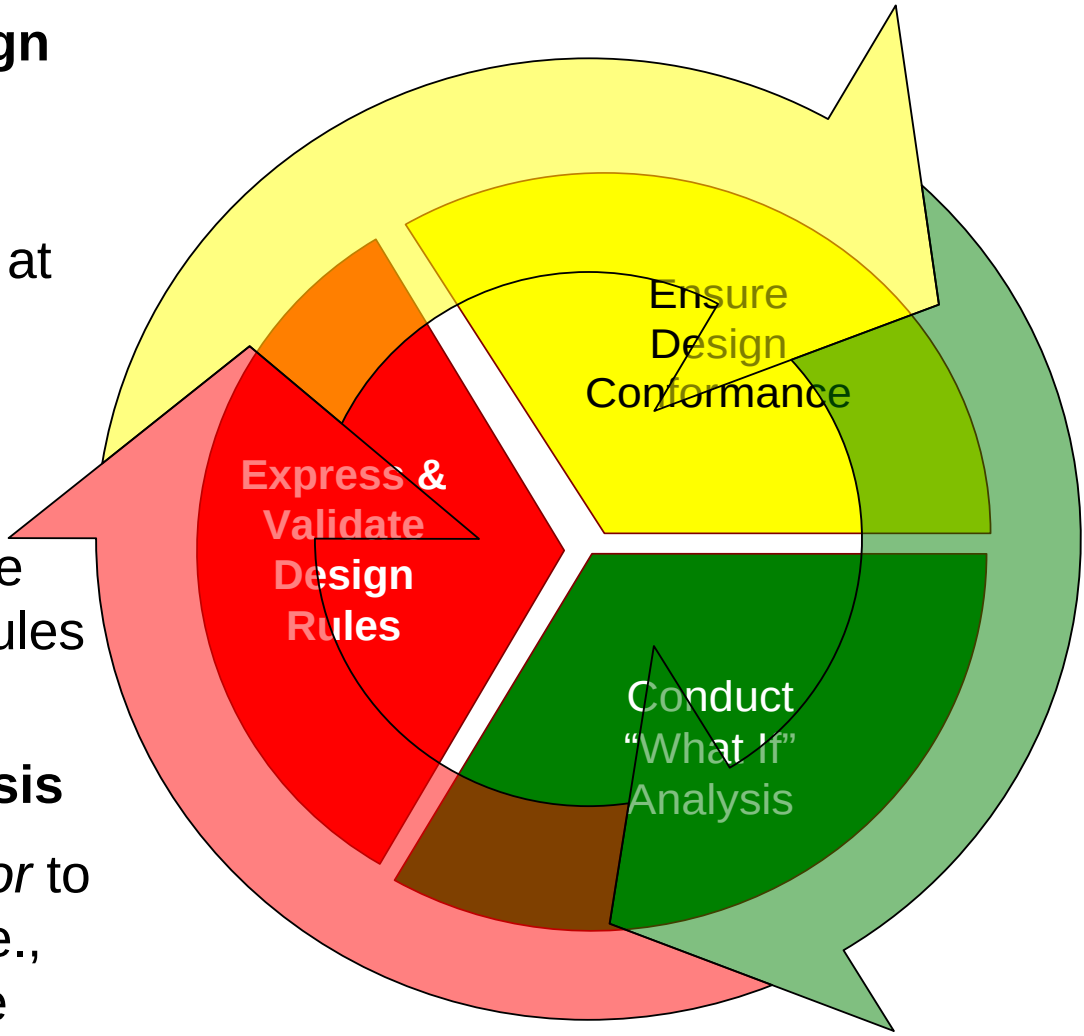
- Help applications & developers adhere to system specifications at design-time

Tools to ensure design rule conformance

- Help properly deploy & configure applications to enforce design rules throughout system lifecycle

Tools to conduct "what if" analysis

- Help analyze QoS concerns *prior* to completing the entire system, i.e., before system integration phase

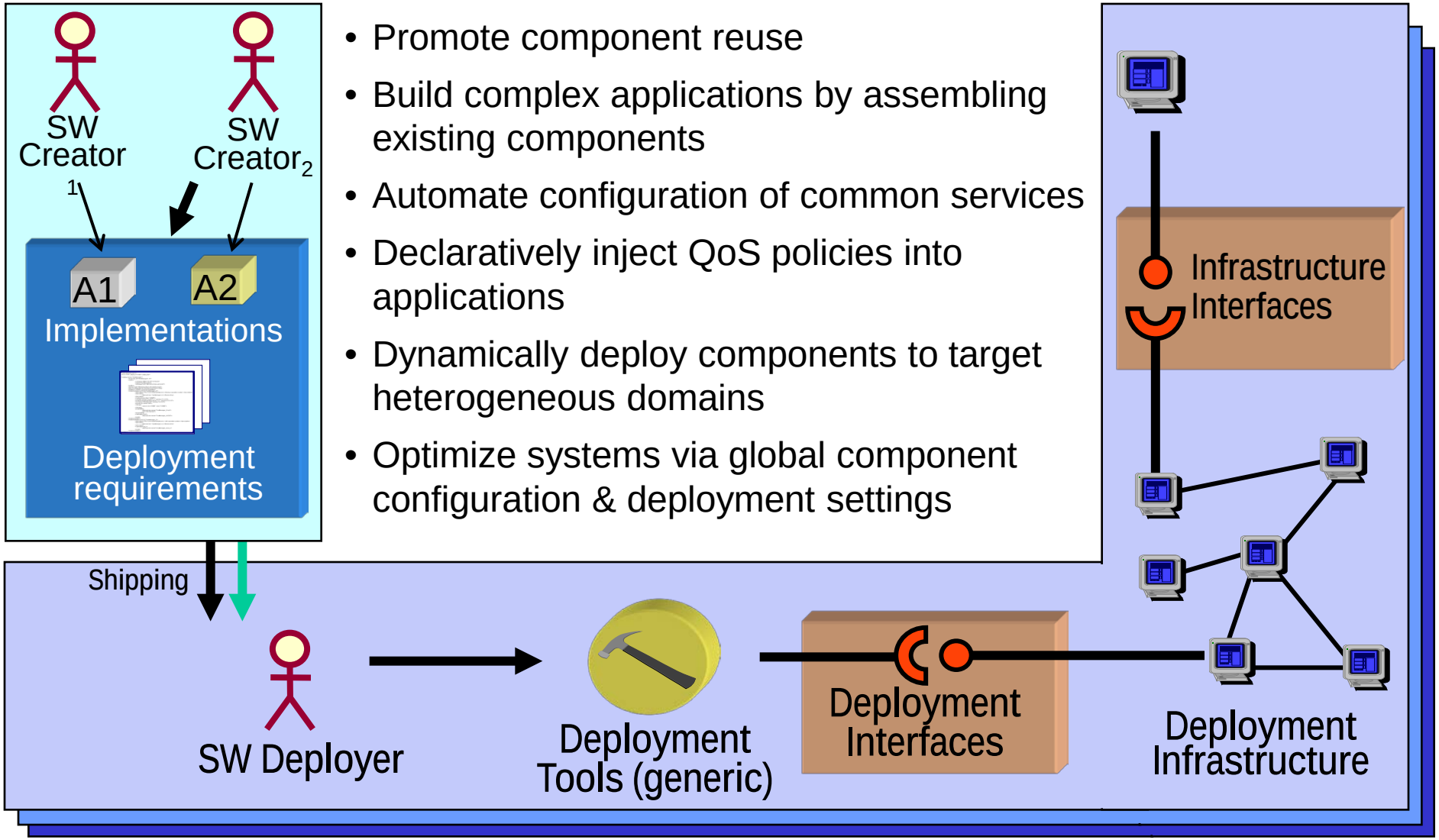


SEM tools should be applied continuously when developing software elements

SEM Tool Example: Component Deployment & Configuration

Deployment & configuration (D&C) Goals

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



SEM Tool Example: Component 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

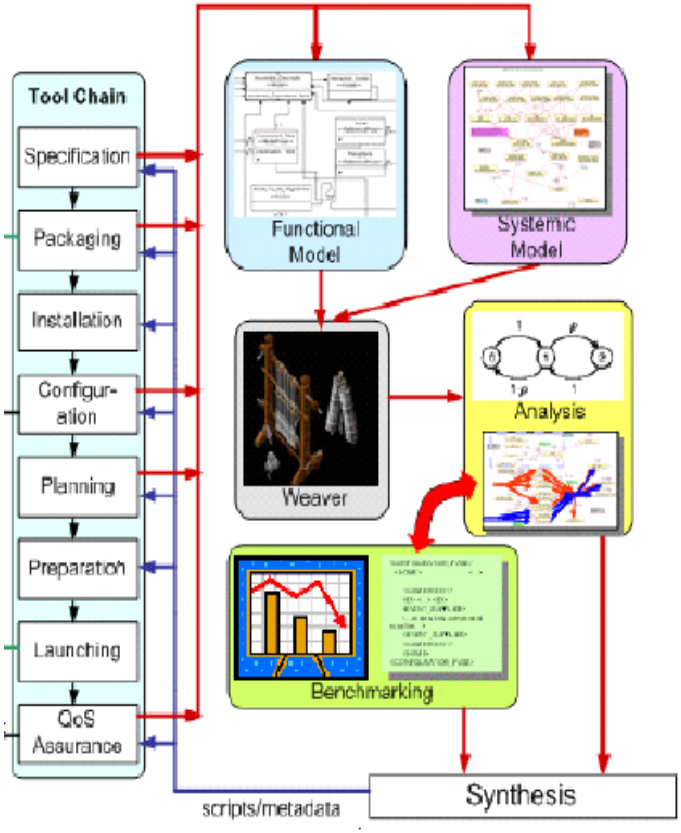
- Moving binaries to identified entities of target environment

Launching

- Triggering installed binaries & bringing app to ready state

QoS Assurance & Adaptation

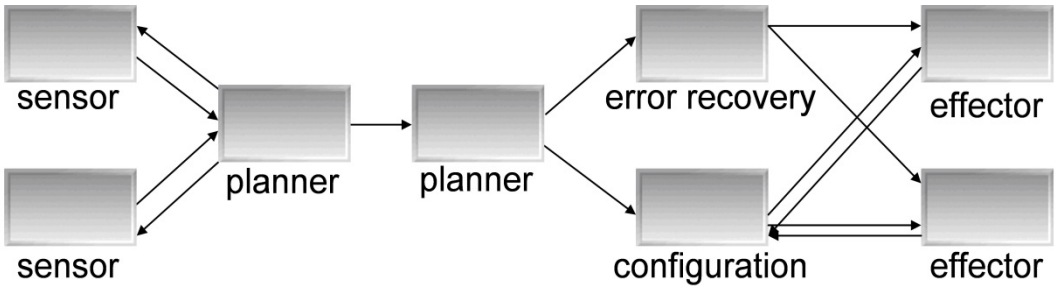
- Runtime (re)configuration & resource management to maintain end-to-end QoS

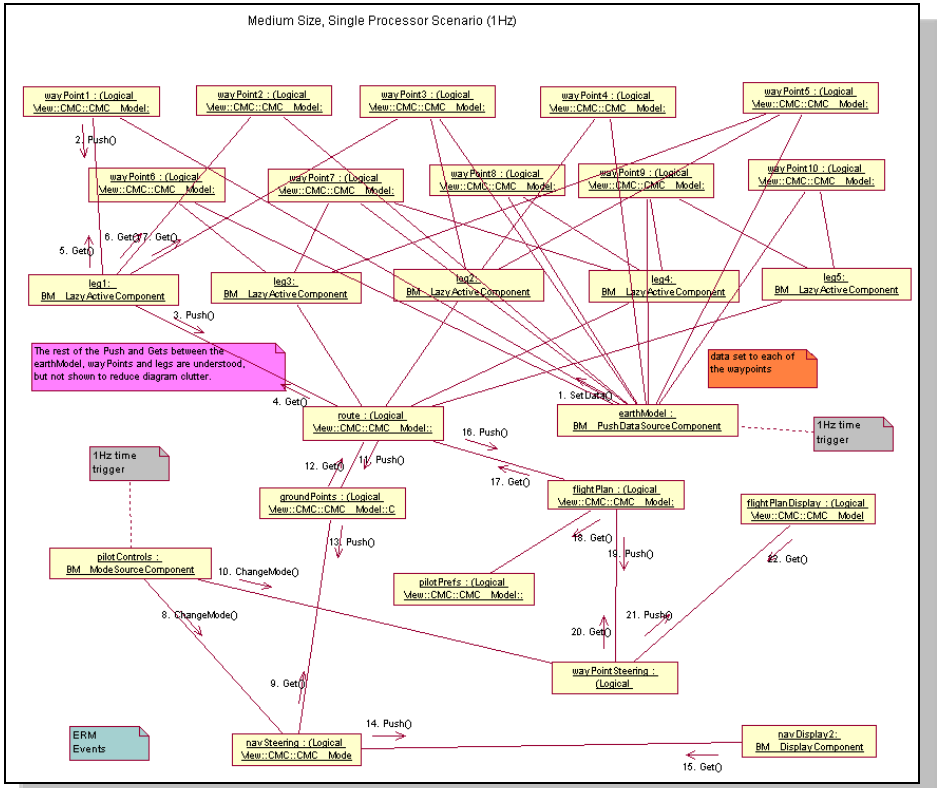


Example D&C specifications include

- OMG Lightweight CORBA Component Model (CCM) &
- IBM Service Component Architecture (SCA)

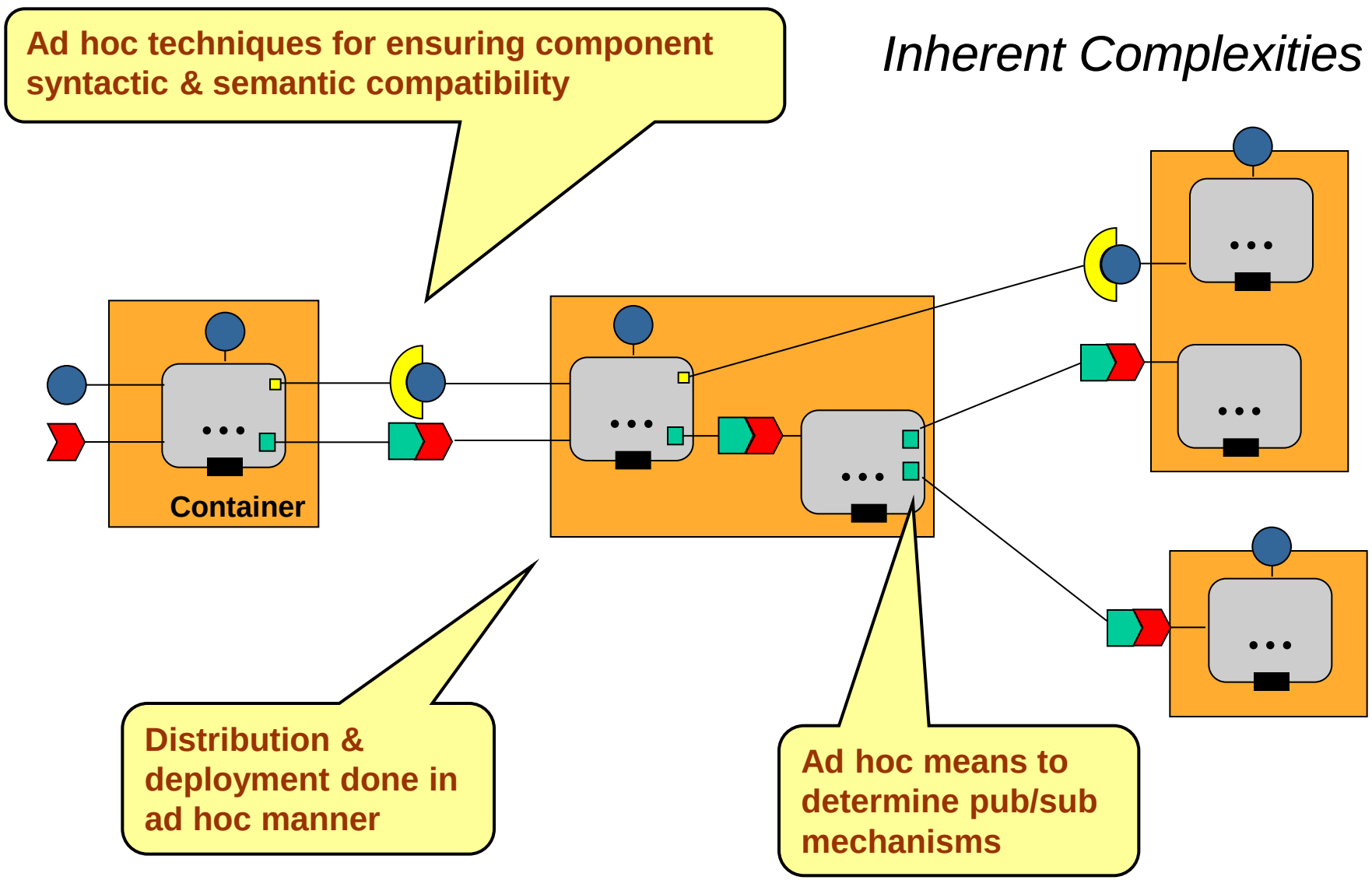
Challenge 1: The Packaging Aspect





- Application components are bundled together into *assemblies*
- Different assemblies tailored to deliver different end-to-end QoS and/or using different algorithms can be part of a package
- ULS systems will require enormous # (10^5-10^7) of components
- Packages describing assemblies can be scripted via XML descriptors

Packaging Aspect Problems (1/2)



Packaging Aspect Problems (2/2)

Accidental Complexities

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

Existing practices involve handcrafting XML descriptors

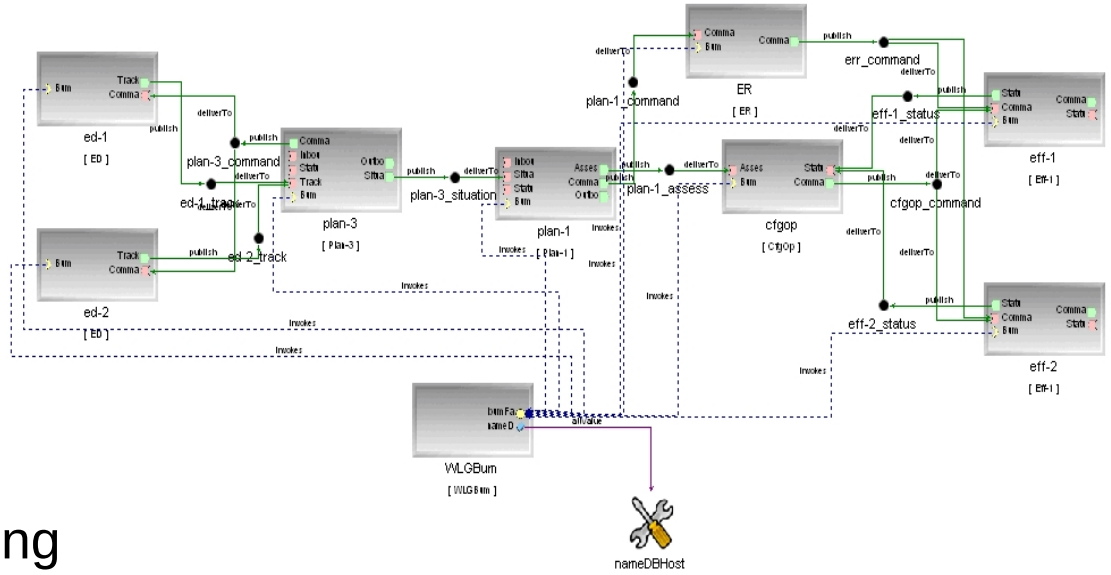
XML file in excess of 3,000 lines, even for medium sized scenarios

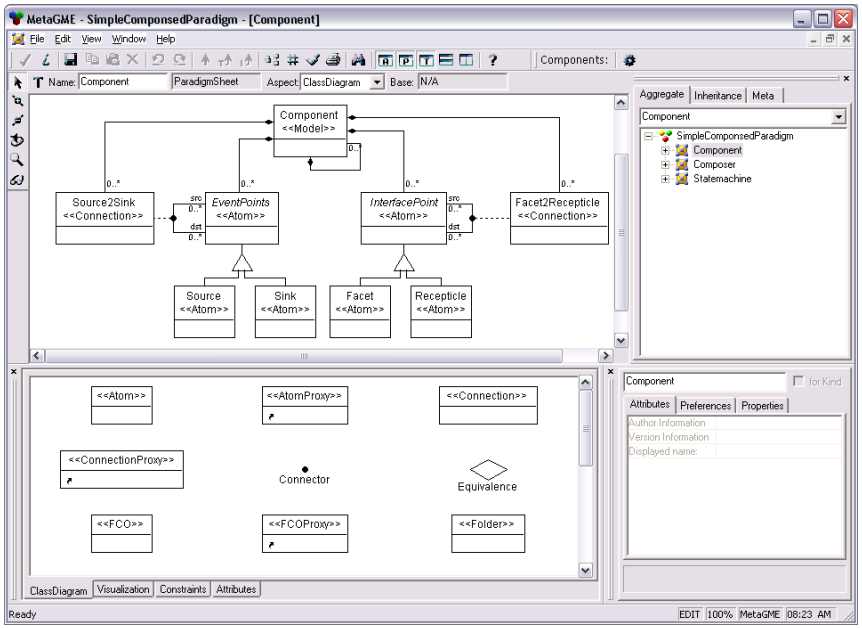
Modifications to the assemblies requires modifying XML file

SEM Tool Approach for Packaging Aspect

Approach:

- Develop the ***Platform-Independent Component Modeling Language*** **(PICML)** to address complexities of assembly packaging
- Capture dependencies visually
- Define semantic constraints using constraints
  - e.g., Object Constraint Language (OCL)
- Generate domain-specific artifacts from models
  - e.g., metadata, code, simulations, etc.
- Uses Generic Modeling Environment (GME) to meta-model & program

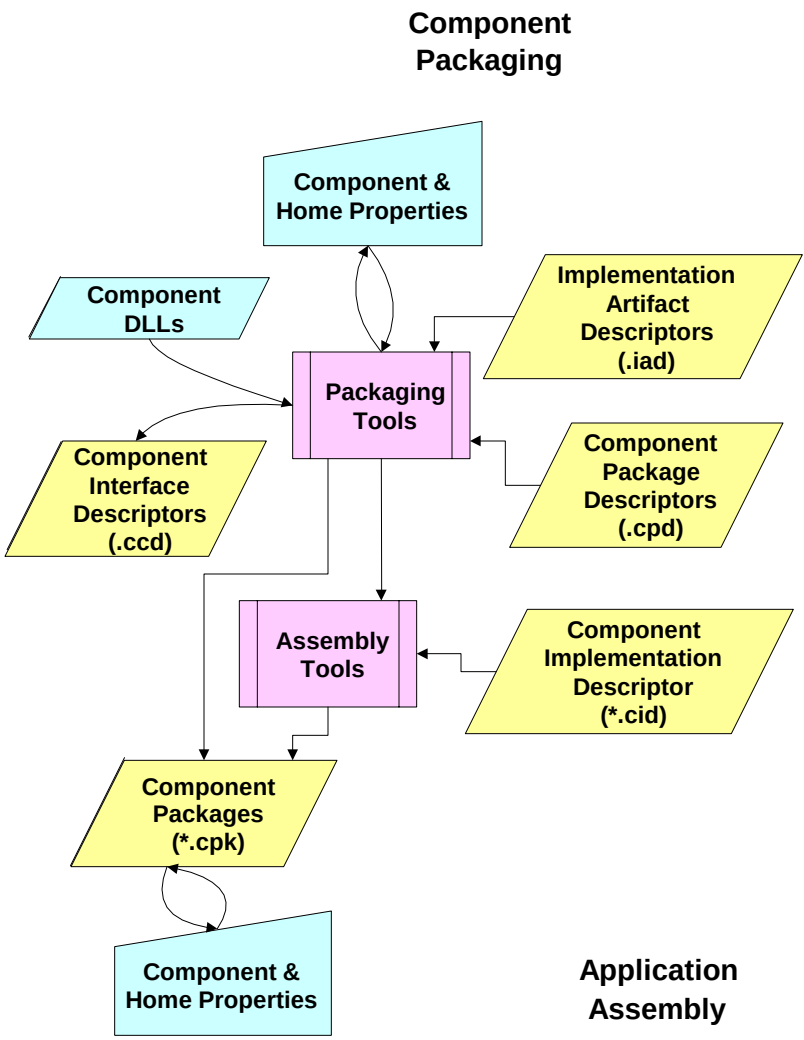




PICML helps to capture & validate design rules for assemblies

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



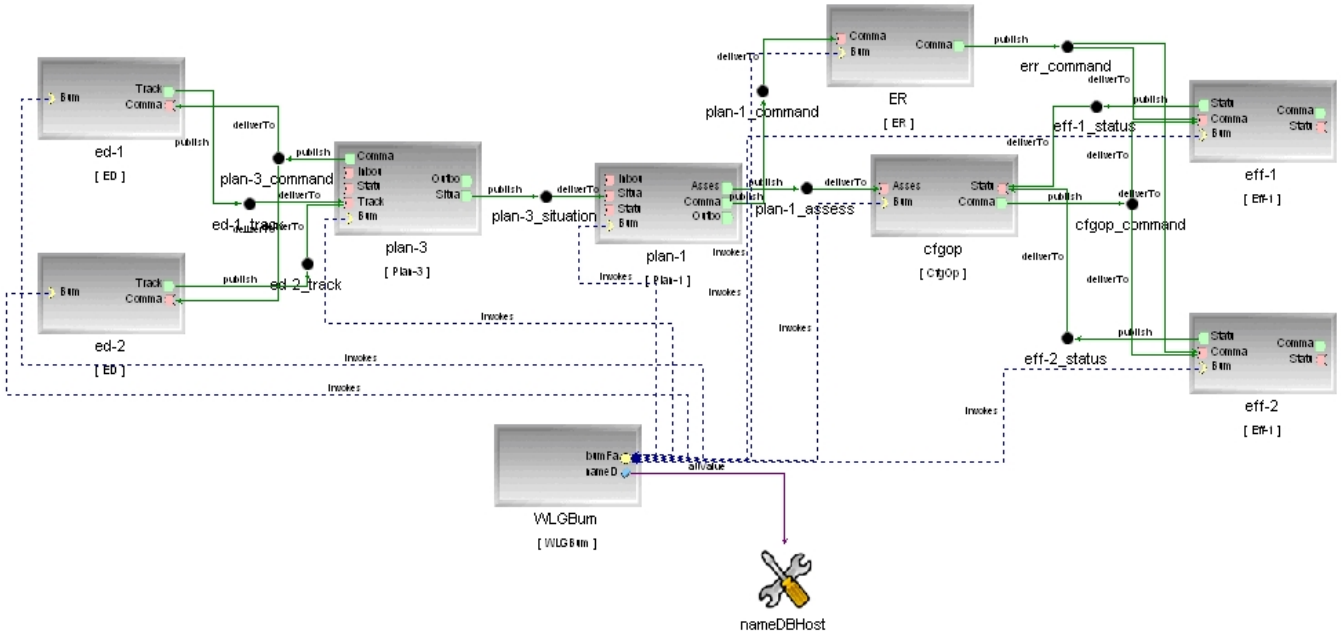
Based on OMG (D&C) specification (ptc/05-01-07)

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

Example Output from PICML Model

A Component Implementation Descriptor (*.cid) file

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



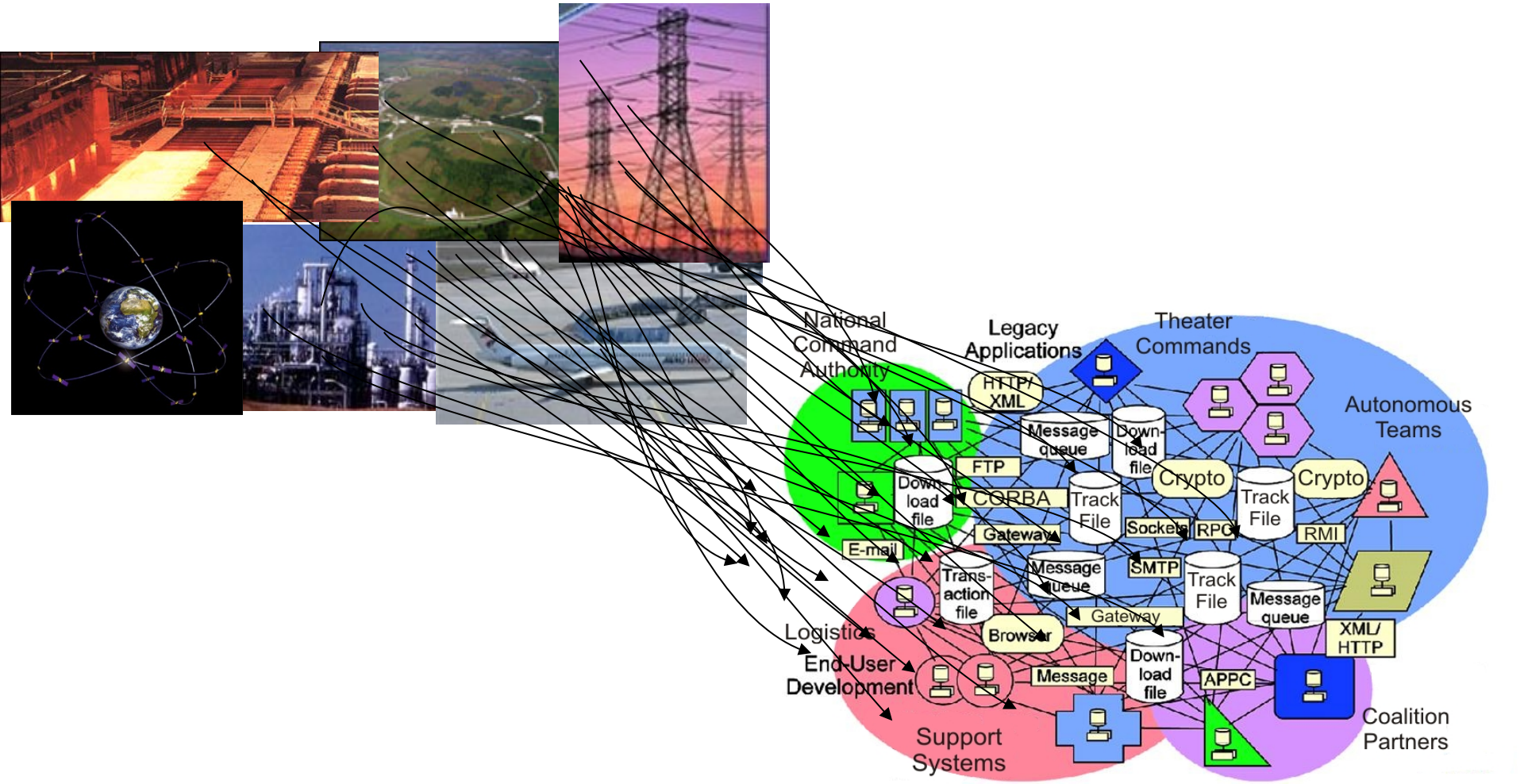

```
<monolithicImpl> [...]
   <deployRequirement>
    <name>Planner</name>
    <resourceType>Planner</resourceType>
    <property><name>vendor</name>
     <value>
       <type> <kind>tk_string</kind> </type>
       <value> <string>My Planner Vendor</string>
     </value>
    </property>
   </deployRequirement> [... Requires VxWorks ...]
 </monolithicImpl>
```

```
<connection> <name>Effector</name>
     <internalEndpoint>
         <portName>Ready</portName>
       <instance href="#Planner"/>
     </internalEndpoint>
     <internalEndpoint>
         <portName>Refresh</portName>
       <instance href="#Effector"/>
     </internalEndpoint>
</connection>
```

PICML supports better expression of domain intent & “correct-by-construction”

Challenge 2: The Configuration Aspect

ULS systems are characterized by a large *configuration space* that maps known variations in the application requirements space to known variations in the software solution space



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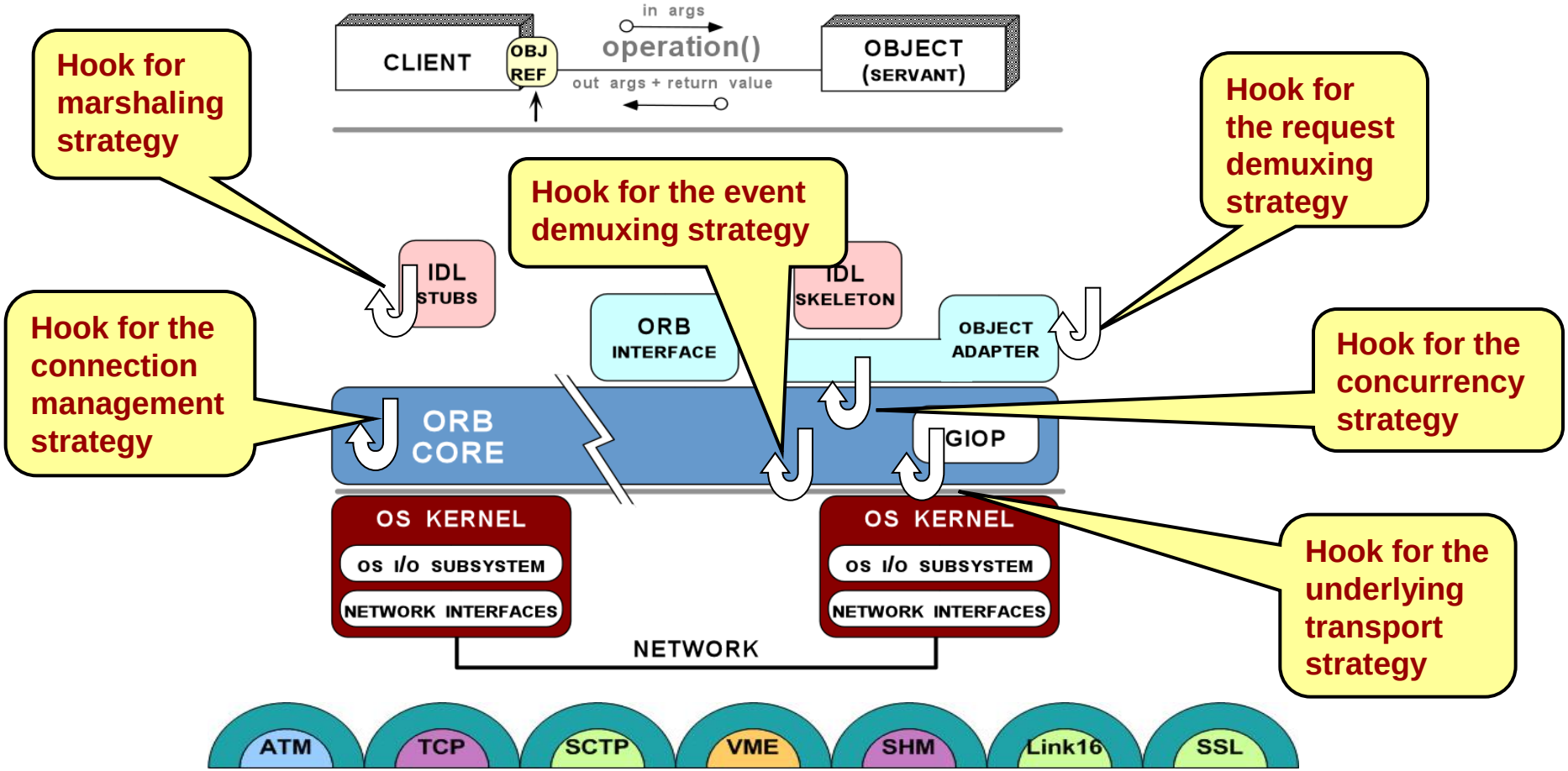
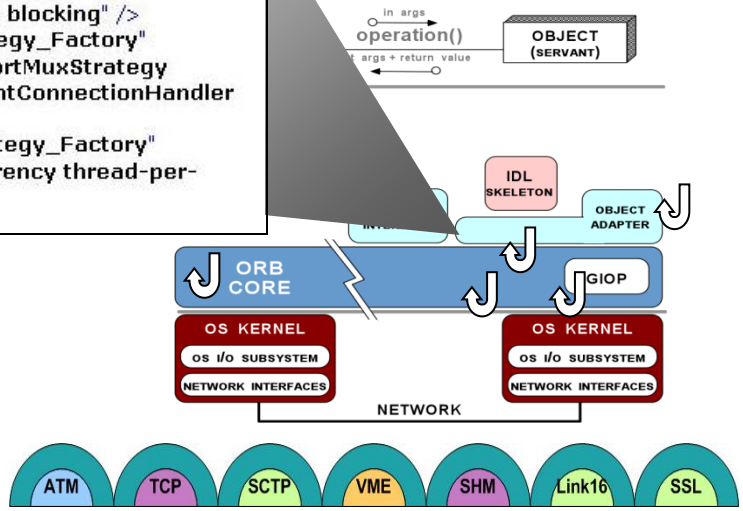


Configuration Aspect Problems

Middleware developers

- Documentation & capability synchronization
- Semantic constraints, design rules, & 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, rules, & semantics
  - Increases accidental complexity
- Different middleware uses different configuration mechanisms
- e.g.

Microsoft .net — XML Configuration Files

JAVA — XML Property Files

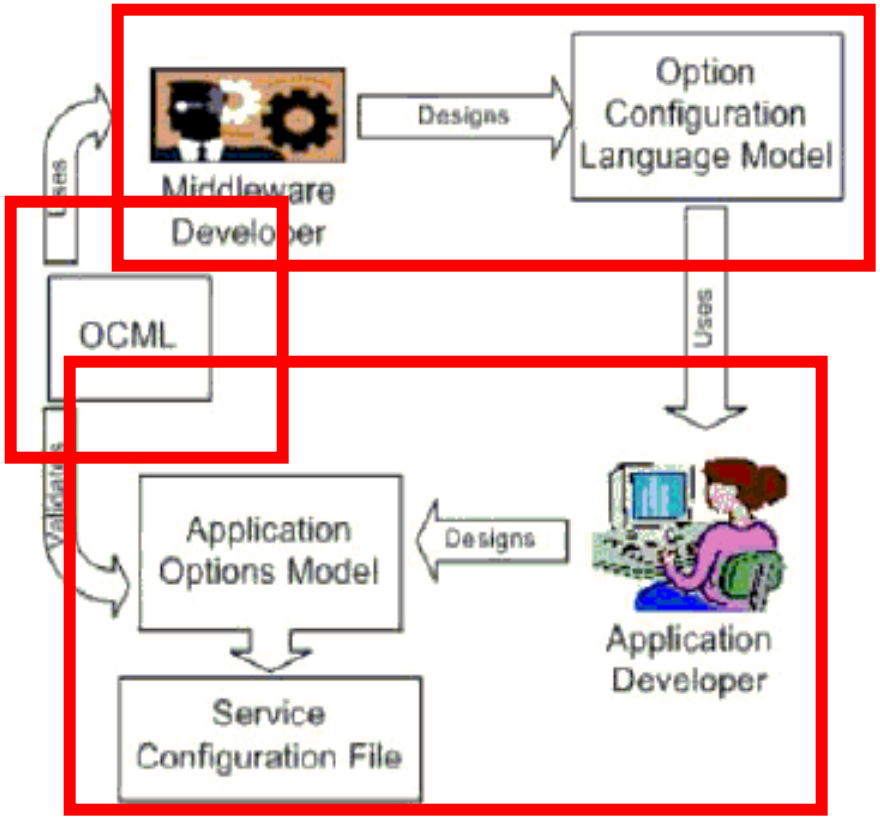
CORBA — CIAO/CCM provides ~500 configuration options

SEM Tool Approach for Configuration Aspect

Approach:

- Develop an ***Options Configuration Modeling Language (OCML)*** to encode design rules & ensure semantic consistency of option configurations

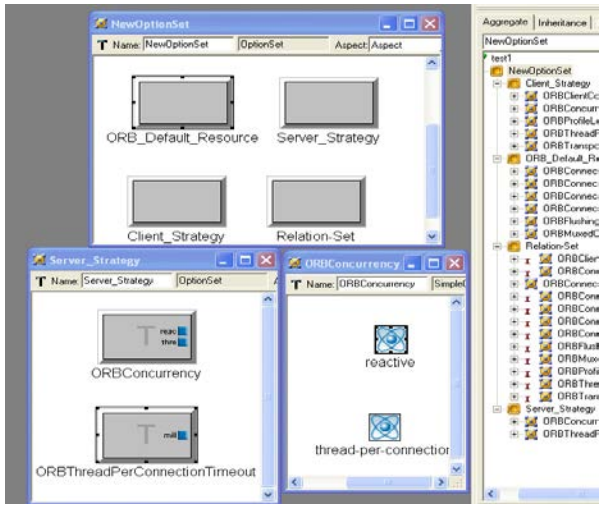
- OCML is used by
  - **Middleware developers** to design the *configuration model*
  - **Application developers** to configure the middleware for a specific application
- OCML *metamodel* is platform-independent
- OCML *models* are platform-specific

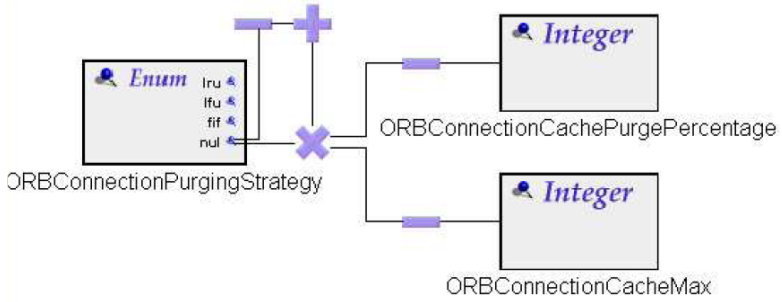


OCML helps to ensure design conformance

Applying OCML to CIAO+TAO

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





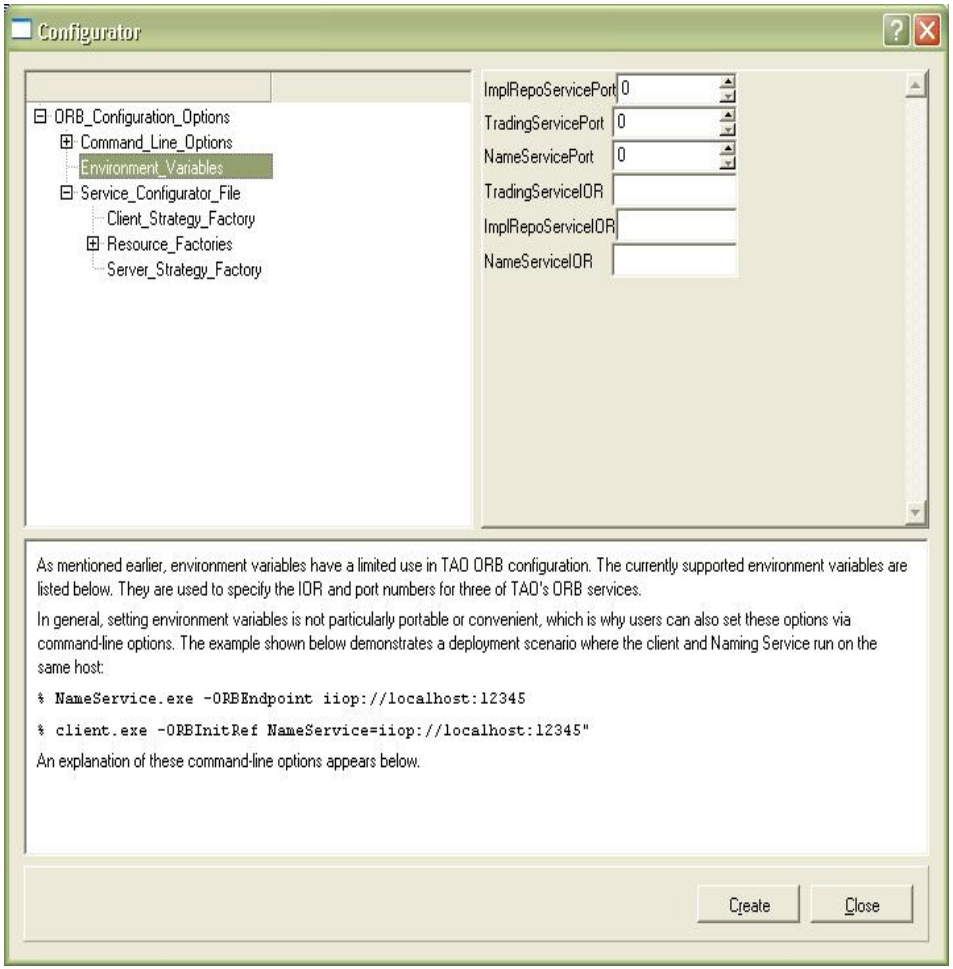

```
<CONFIGURATION>
   <PROCESSOR>
      <NAME>OCP_P1</NAME>
      <CONFIGURATION_PASS>
         <HOME>
            <HOME_TYPE>  BM_OPEN_ED_COMPONENT </HOME_TYPE>
            <ID>
               <GROUP_ID> 20 </GROUP_ID>
               <ITEM_ID>  22 </ITEM_ID>
               <NAME>     BM_OPEN_ED_COMPONENT  </NAME>
            </ID>
            <COMPONENT>
               <ID>
                  <GROUP_ID>200</GROUP_ID>
                  <ITEM_ID>220</ITEM_ID>
                  <NAME>WAYPOINT_PROXY</NAME>
               </ID>
               <DISTRIBUTION>
                  <DIST_WRITE>
                     <PROXY>
                        <ID>
                           <GROUP_ID>200</GROUP_ID>
                           <ITEM_ID>221</ITEM_ID>
                           <NAME>WAYPOINT</NAME>
                        </ID>
                     </PROXY>
                  </DIST_WRITE>
               </DISTRIBUTION>
               <EVENT_SUPPLIER>
                  <EVENT_SET>
                     <EVENT>
```

```
/**
 * Return the last time the client sent a request associated
 * session, as the number of ms since midnight, Jan 1, 1970
 * GMT.  Actions your application takes, such as get or set
 * value associated with session, do not affect access time.
 */
public long getLastAccessedTime() {
   return (this.lastAccessedTime);
}

/**
 * Update the accessed time information for this session.
 * Method is called by context when request comes in for a
 * session, even if the application does not reference it.
 */
public void access() {
   this.lastAccessedTime = this.thisAccessedTime;
}
```

Applying OCML to CIAO+TAO

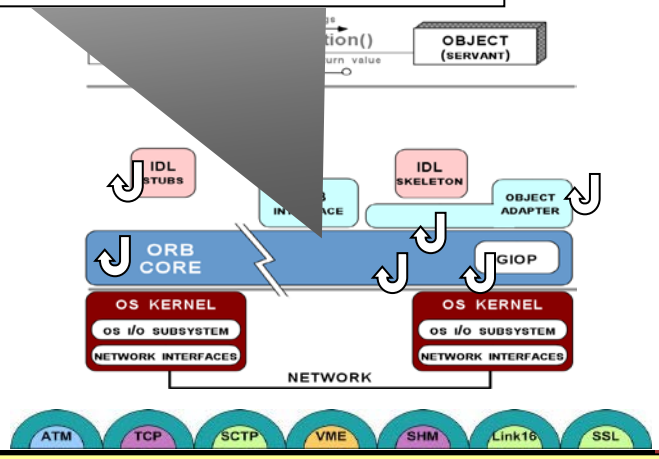
- Middleware developers specify
  - Configuration space
  - Constraints
- OCML generates config model
- Application developers provide a model of desired options & their values, e.g.,
  - Network resources
  - Concurrency & connection management strategies



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

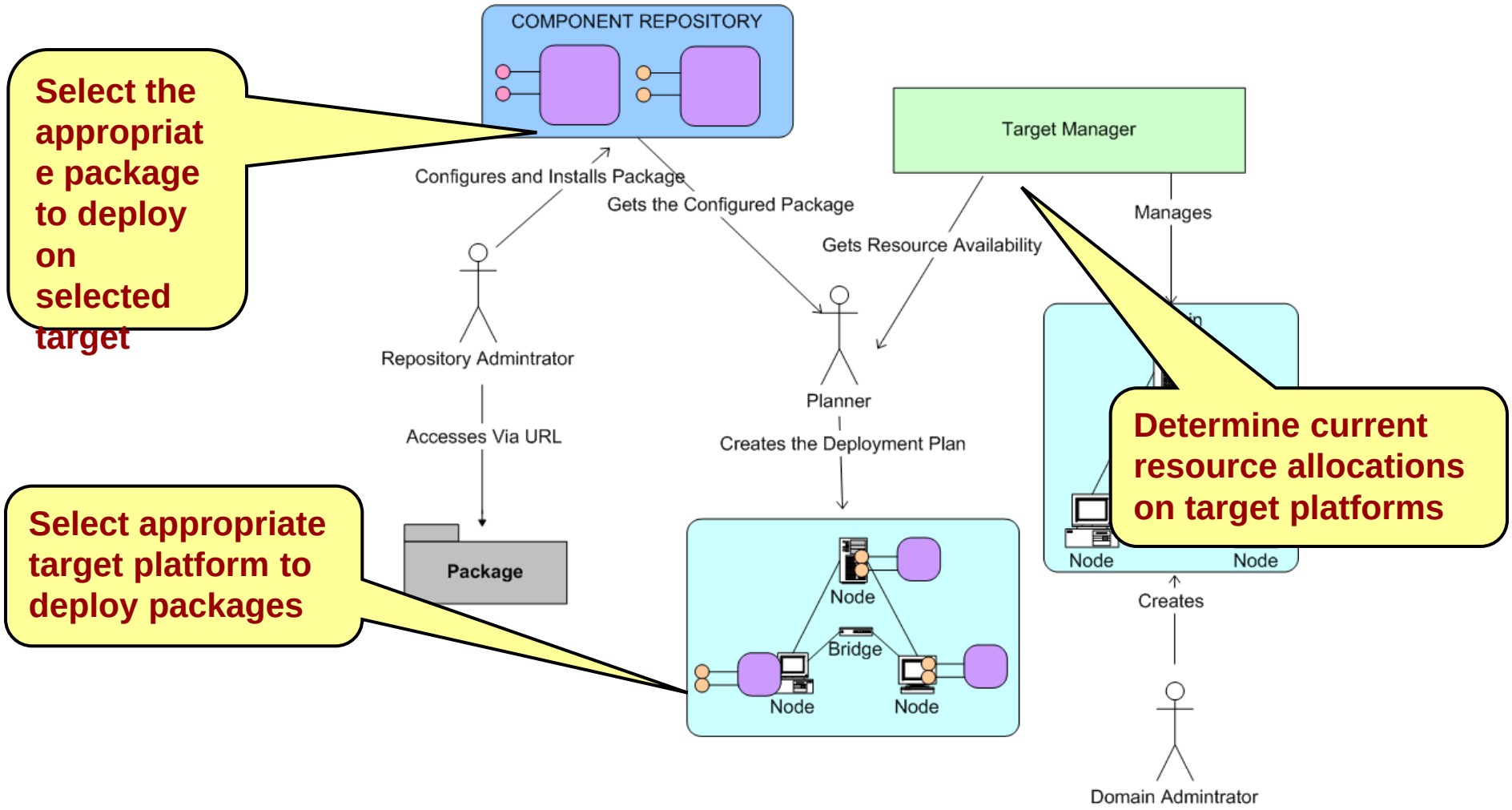
```
ests/Latency/Thread_Per_Connection/svc.conf
ACE_Svc_Conf>
 <!--     -->
 <!--   $Id: svc.conf.xml,v 1.1 2002/08/23
 22:23:04 nanbor Exp $   -->
 <!--     -->
 <static id="Advanced_Resource_Factory"
   params="-ORBReactorType select_mt -
   ORBReactorMaskSignals 0 -
   ORBFlushingStrategy blocking"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



OCML automates activities that are very tedious & error-prone to do manually

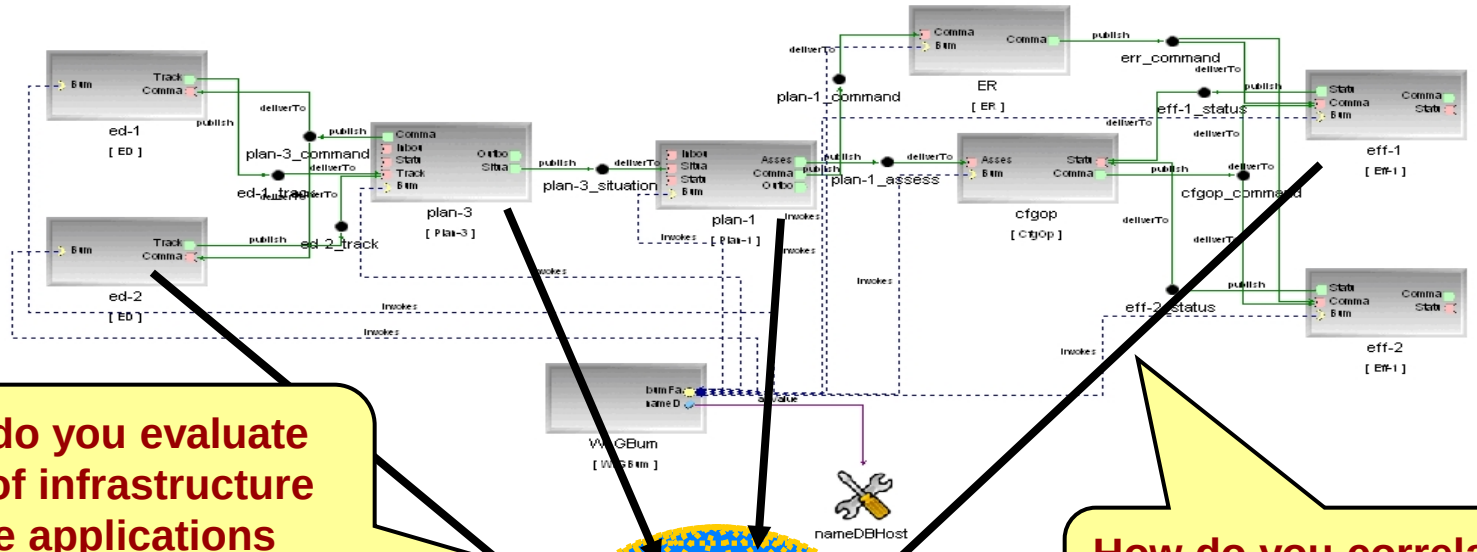
Challenge 3: Planning Aspect

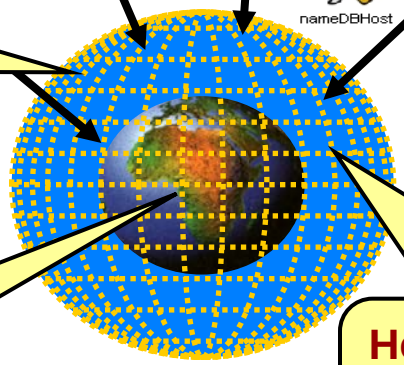
System integrators must make appropriate deployment decisions, identifying nodes in target environment where packages will be deployed



Planning Aspect Problems

Ensuring deployment plans meet ULS system QoS requirements





How do you evaluate QoS of infrastructure before applications are completely built?

How do you correlate QoS requirements of packages to resource availability?

How do you determine current resource allocations?

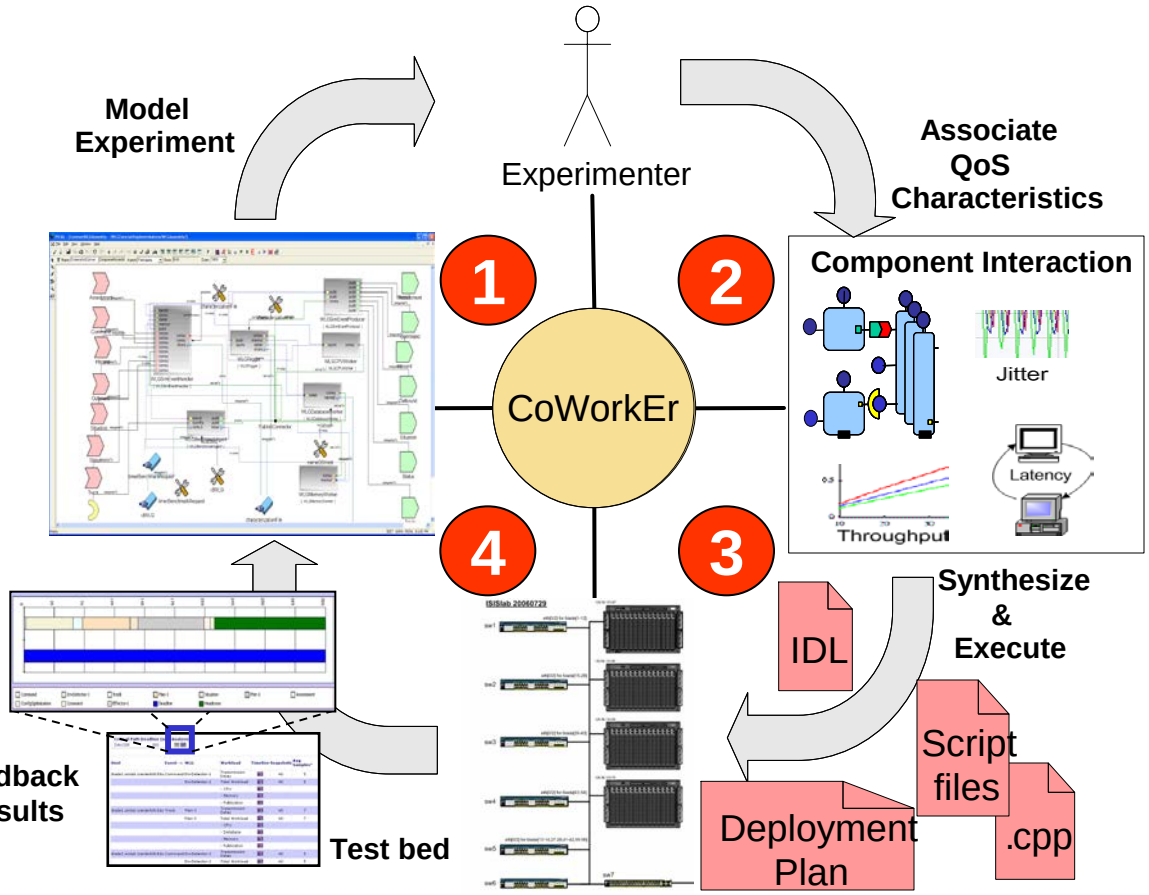
How do you ensure that selected targets will deliver required QoS?

SEM Tool Approach for Planning Aspect

Approach

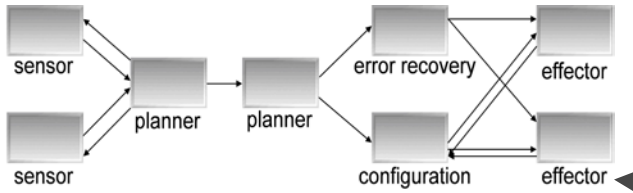
- Develop ***Component Workload Emulator (CoWorkEr) Utilization Test Suite (CUTS)*** to allow architects & systems engineers to

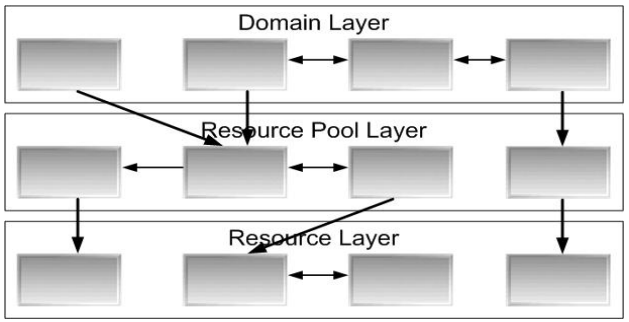
1. Compose scenarios to exercise critical system paths
2. Associate performance properties with scenarios & assign properties to components specific to paths
3. Configure workload generators to run experiments, generate deployment plans, & measure performance along critical paths
4. Analyze results to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

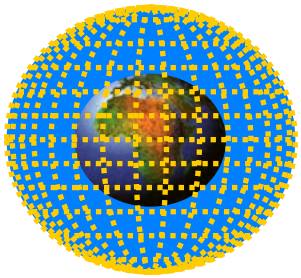


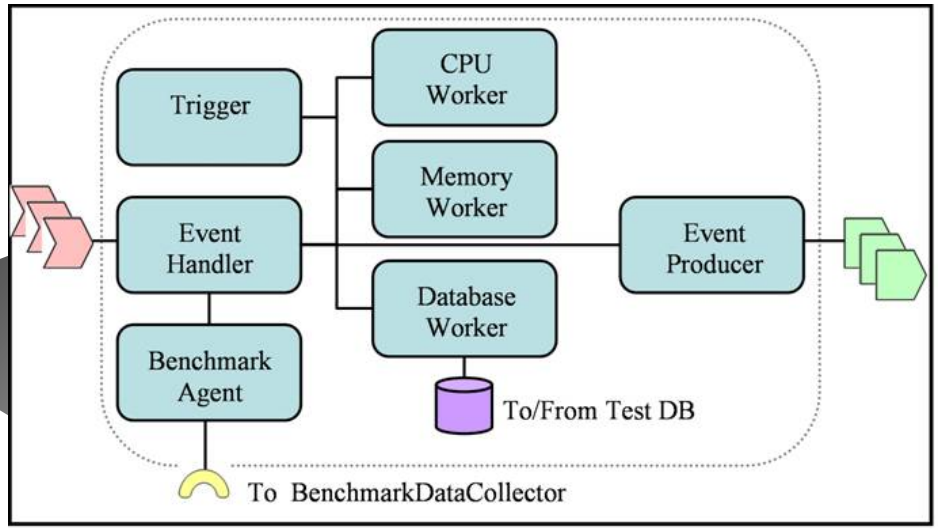
CUTS helps to conduct "what if" analysis on evolving systems

Emulating Computational Components in CUTS







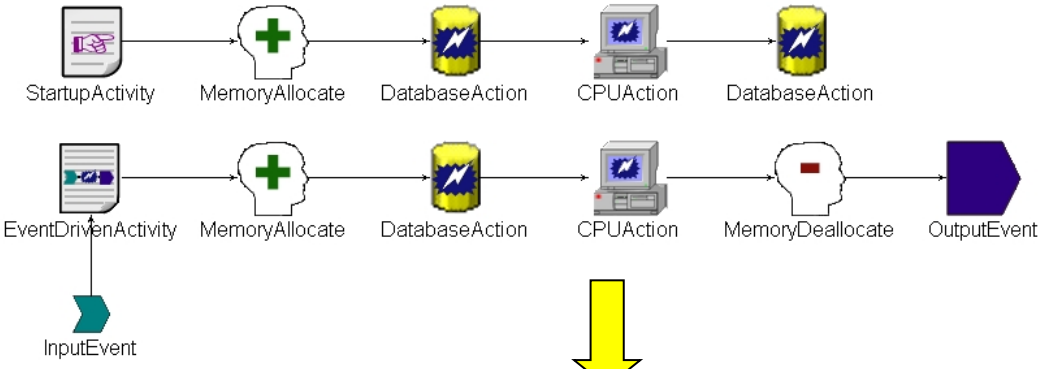


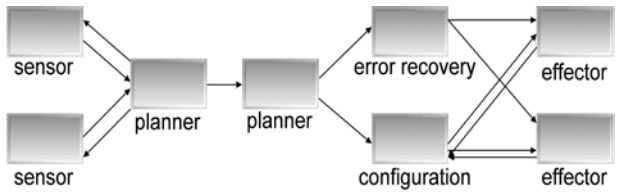
- Application components are represented as *Component Workload Emulators* (*CoWorkErs*)
- *CoWorkErs* can be interconnected by the *PICML* tool to form *operational strings*

Level of Abstraction

Development Timeline

Representing Computational Components in CUTS



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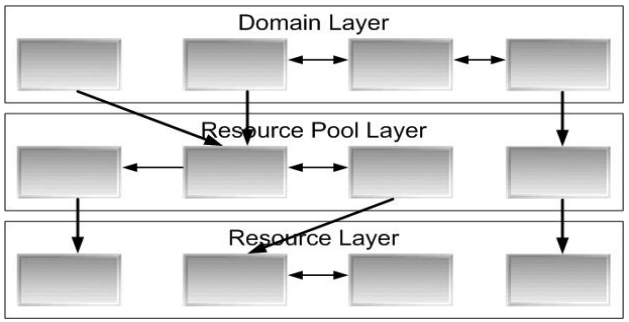
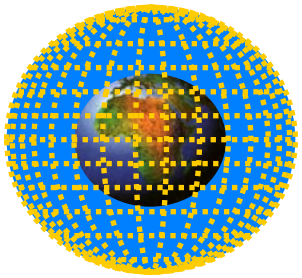


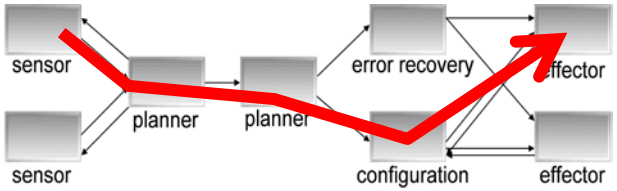


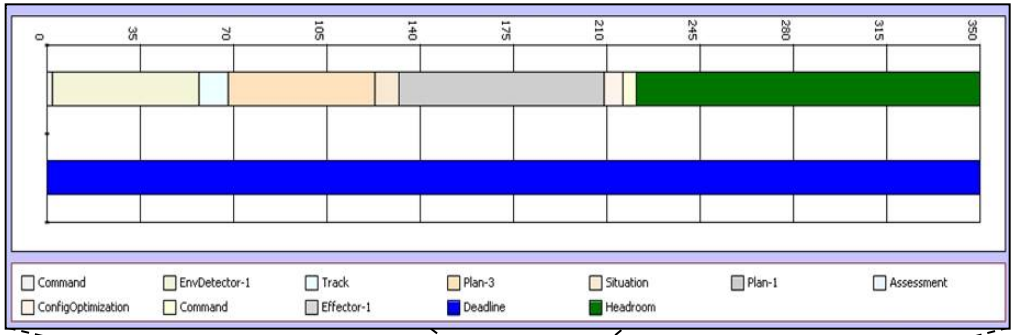
- *Workload Modeling Language (WML)* MDE tool defines behavior of *CoWorkEr*s via "work sequences"
- WML programs are translated into XML characterization files
- These files then configure *CoWorkEr*s

Level of Abstraction

Development Timeline

Visualizing Critical Path Performance in CUTS

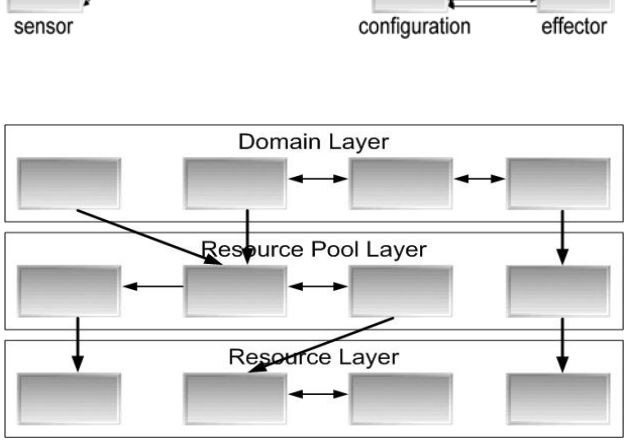


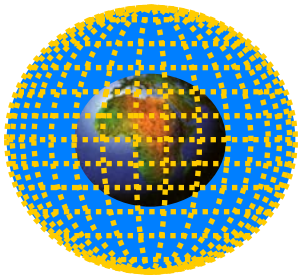


Critical Path Deadline (ms) Analysis

DAnCER 350

Host	Event ->	WLG	Workload	Timeline	Snapshots	Avg Samples*
blade1.isislab.Vanderbilt.Edu	Command	EnvDetector-1	Transmission Delay		40	5
		EnvDetector-1	Total Workload		40	5
			- CPU			
			- Memory			
			- Publication			
blade1.isislab.Vanderbilt.Edu	Track	Plan-3	Transmission Delay		40	7
		Plan-3	Total Workload		40	7
			- CPU			
			- Database			
			- Memory			
			- Publication			
blade3.isislab.Vanderbilt.Edu	Command	EnvDetector-2	Transmission Delay		40	5
		EnvDetector-2	Total Workload		40	5





Level of Abstraction

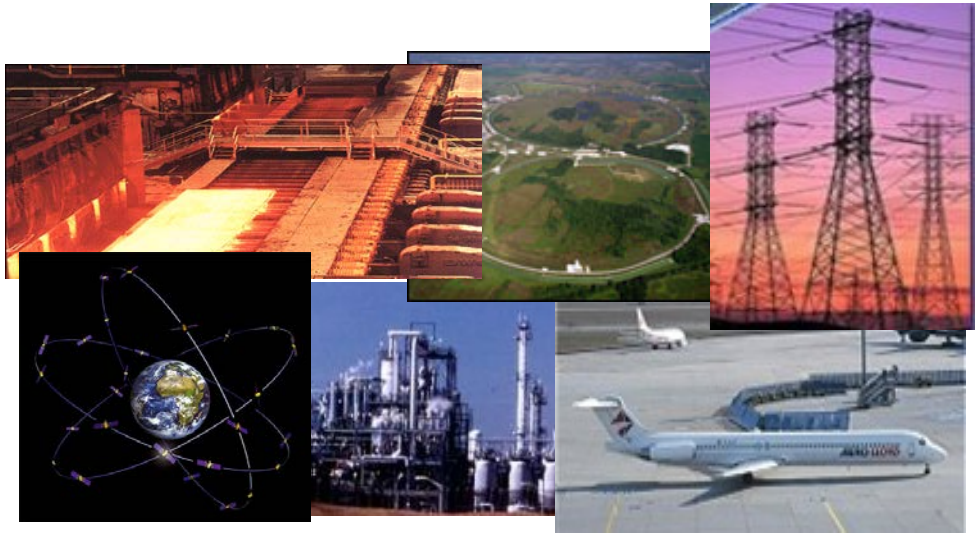
Development Timeline

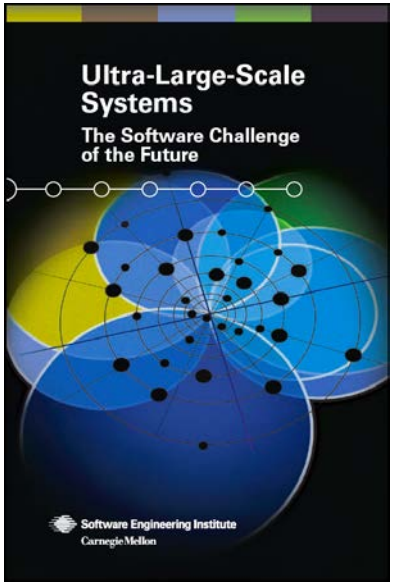
- *BenchmarkManagerWeb-interface (BMW)* MDE tool generates statistics showing performance of actions in each *CoWorkEr*
- Critical paths show end-to-end performance of mission-critical operational strings

CUTS integrates nicely with *continuous integration servers*

Concluding Remarks

- The emergence of ULS systems requires significant innovations & advances in tools & platforms
- Not all technologies provide the precision we're accustomed to in legacy real-time systems
- Advances in Model-driven engineering (MDE) are needed to address ULS systems challenges
- Significant MDE groundwork laid in recent DARPA programs





- Much more R&D needed for ULS systems
  - e.g., recent Software Engineering Institute study

ULS systems report available at www.sei.cmu.edu/uls