The Real-Time UML Standard: Theory and Application

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Tutorial Objectives

- To clarify the relationship between the object paradigm and real-time systems
  - match or mismatch?
- Describe and analyze UML from a real-time designer's perspective
- To introduce the *"UML Profile for Schedulability, Performance, and Time"*
- To introduce an *engineering-oriented design* approach for real-time systems

Tutorial Overview

- Real-Time Systems and the Object Paradigm
- UML as a Real-Time Modeling Language
- The Real-Time UML Profile
- Engineering-Oriented Design of Real-Time Systems
- Summary and Conclusions

- Real-Time Systems and the Object Paradigm
  - Real-Time System Essentials
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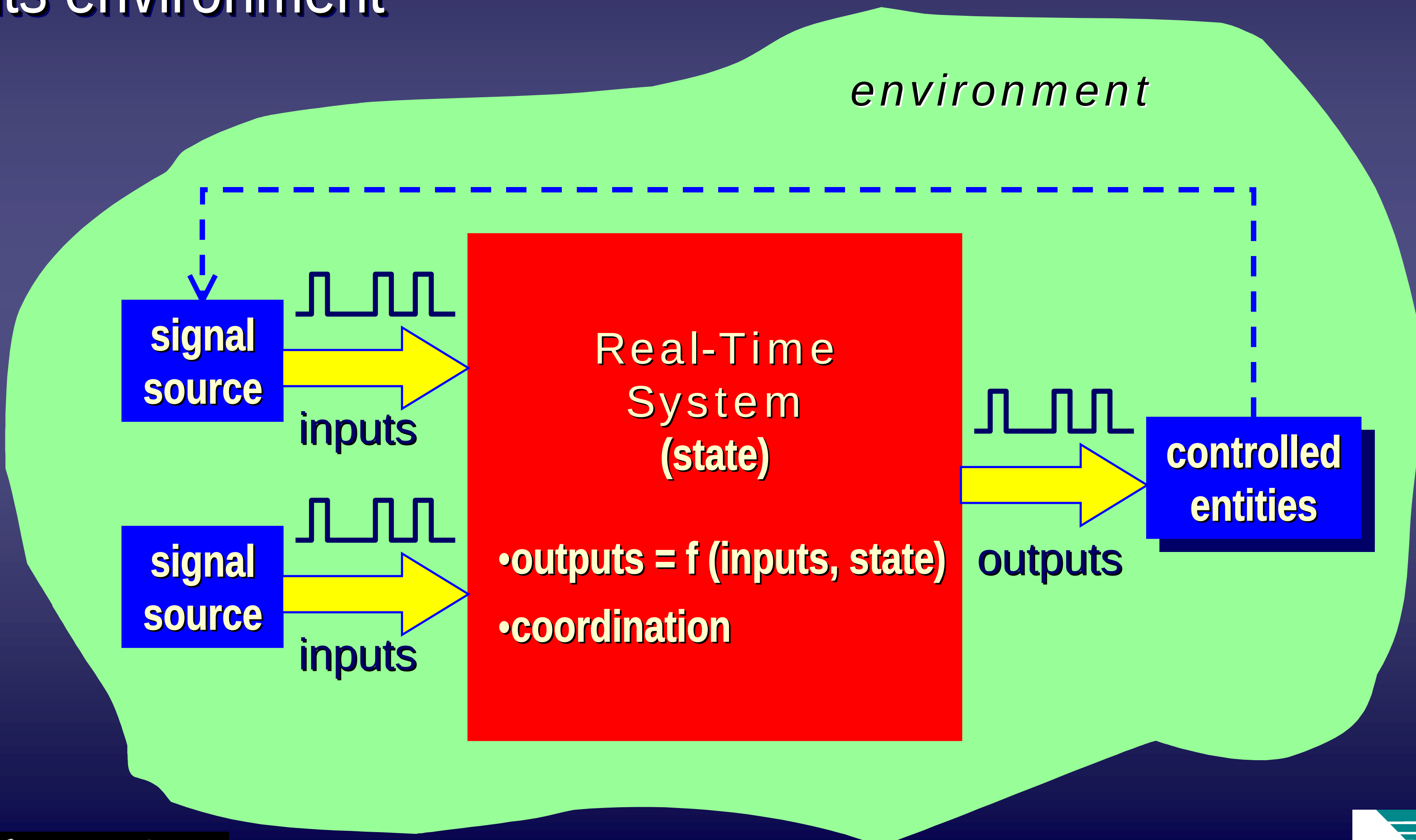
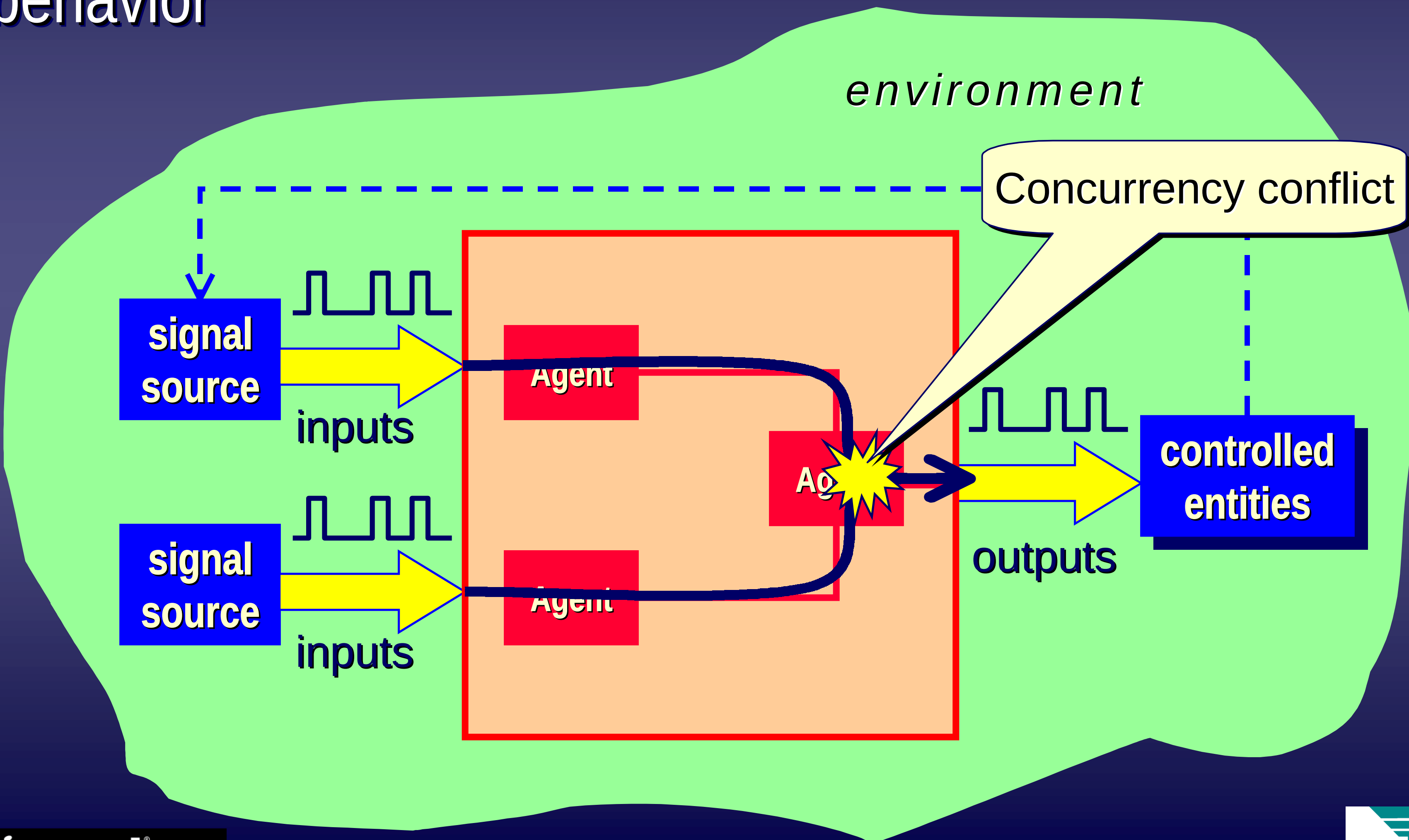
Real-Time System

- Systems that maintain an *ongoing timely* interaction with its environment



Under the Hood

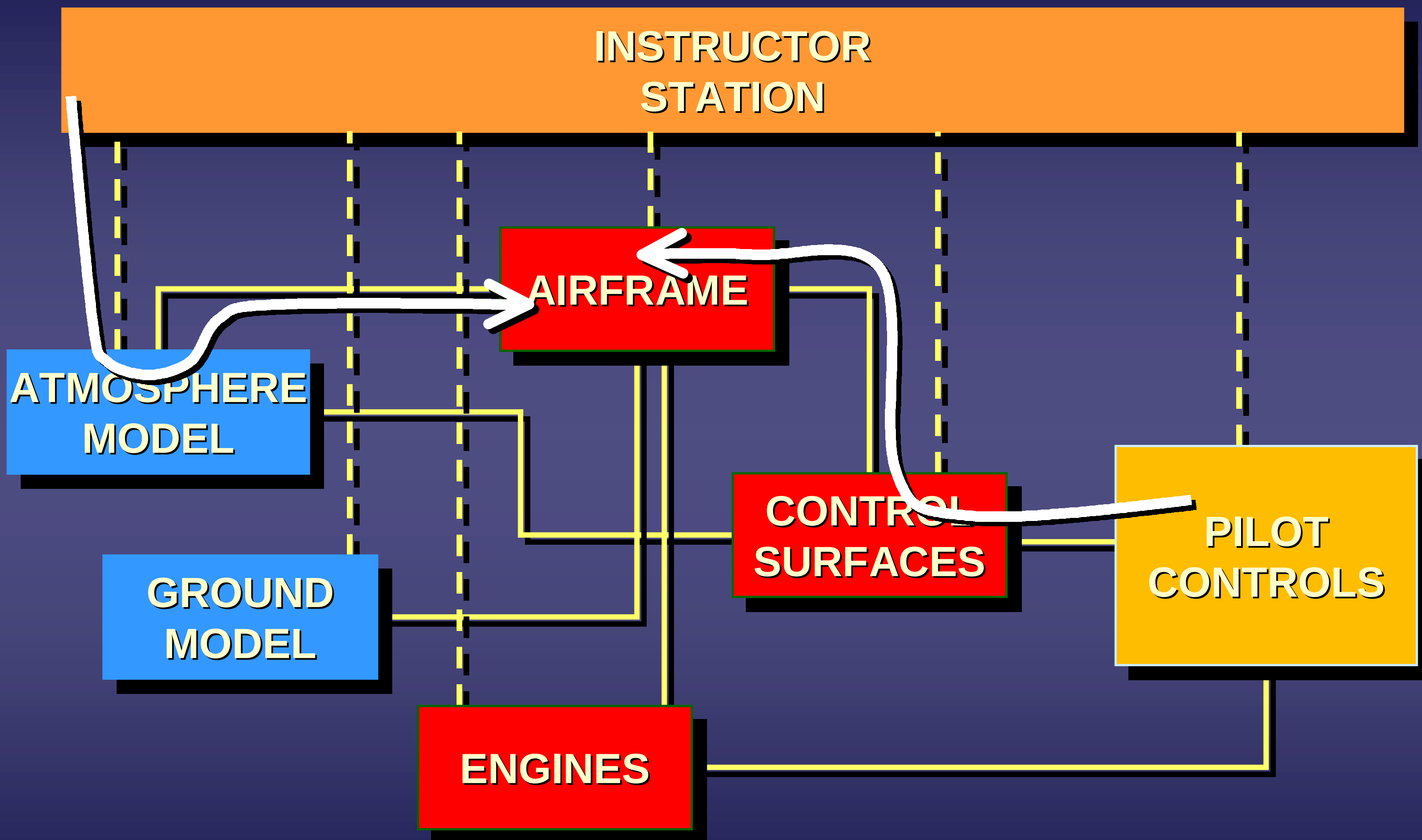
- A persistent structure that provides a framework for behavior



Classifications of RT Systems

- Based on nature of key inputs
  - *time-driven:* for continuous (synchronous) inputs
  - *event-driven:* for discrete (asynchronous) inputs
- Based on time criticality
  - *hard RT systems:* every input must have a timely response
  - *soft RT systems:* most inputs must have timely response
- Based on load:
  - *static:* fixed deterministic load
  - *dynamic:* variable (non-deterministic) load
- Many practical systems are combinations of these

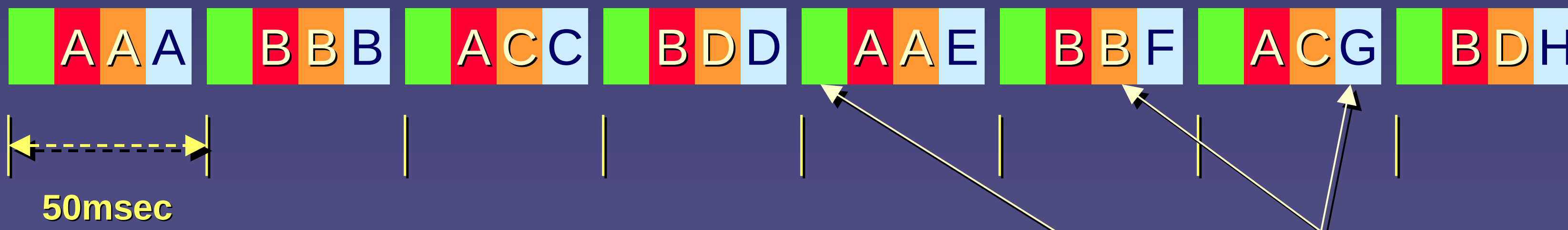
Sample Real-Time Application

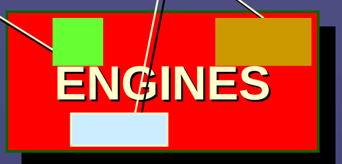


Which procedure(s) describe this system?

Classical Approach: Cyclical Executive

The miscellaneous procedural slices are executed cyclically based on time resolution





= 50 msec band

= 100 msec band (2 parts: A and B)

= 200 msec band (4 parts: A, B, C, D)

= 400 msec band (8 parts: A, B, C, D, E, F, G, H)

The crucially important system structure is almost completely obscured

Problems with the Traditional Solution

- The solution is adjusted to fit the implementation technology (i.e., the step-at-a-time programming style of procedural programming) rather than human needs

⇒ In addition to the inherent complexity of the problem designers need to contend with the accidental complexity of the implementation technology

- Overwhelming complexity is by far the biggest hurdle in most real-time software systems

reducing complexity is crucial to success

- Real-Time Systems and the Object Paradigm
  - Real-Time System Essentials
  - Essentials of the Object Paradigm
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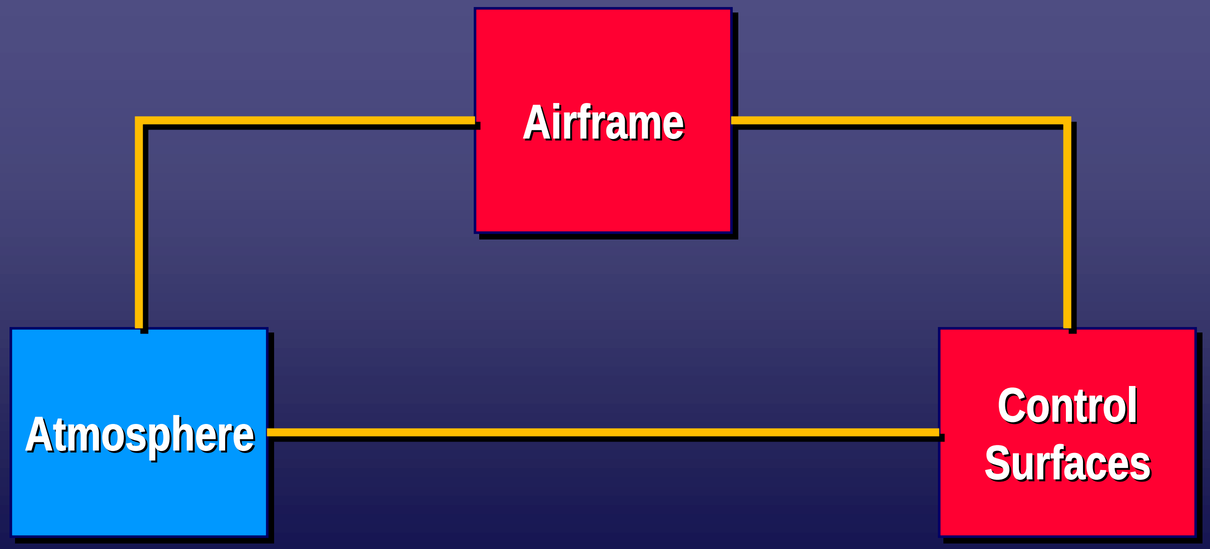
The Essence of the Object Paradigm

- Combines all the various features of a logical unit (procedures and data) into a single package called an *object*
- Defines a software system as *a structure of collaborating objects*



Objects and Real-Time Systems

- The structure of real-time systems tends to persist through time because it reflects the physical entities of the real world
- This structure is the framework through which (infinitely) many different behavior threads are executed
- Hence, the focus is on structure rather than behavior
- *The structural focus of the object paradigm is better suited to real-time systems than the procedural paradigm*

Yes, But What About...

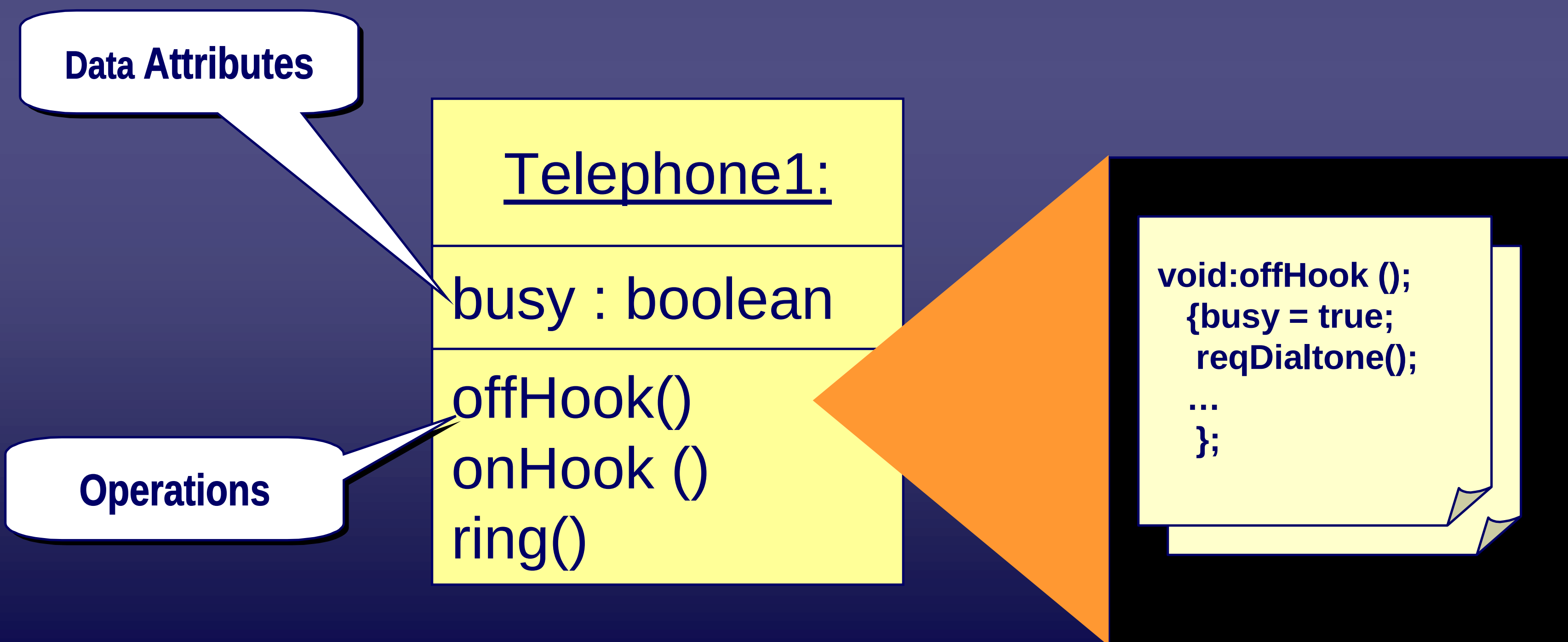
- Performance?
  - the cost of abstraction (encapsulation, automatic garbage collection, dynamic binding, etc.)
- Modeling real-time specific phenomena?
  - time and timing mechanisms
  - resources (processors, networks, semaphores, etc.)
- Exploiting current real-time system theory?
  - schedulability analysis (e.g., rate-monotnic theory)
  - performance analysis (queueing theory)

Performance of OO Technology

- Hardware is becoming ever faster (Moore's law)
  - previously unacceptable response times may now be acceptable
- OO software technologies are becoming real-time aware
  - bounded dynamic binding techniques
  - tunable automatic garbage collection (bounded latency)
  - real-time variants of popular OO languages (e.g., EC++, RT Java)

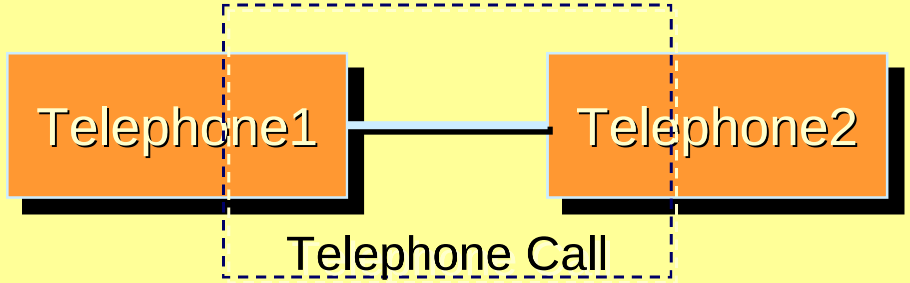
Objects

- Conceptual units with
  - a unique identity (dedicated memory)
  - a public interface
  - a hidden (encapsulated) implementation



Conceptual Objects

- Not all objects necessarily require a physical underpinning
- For example, the “telephone call” object



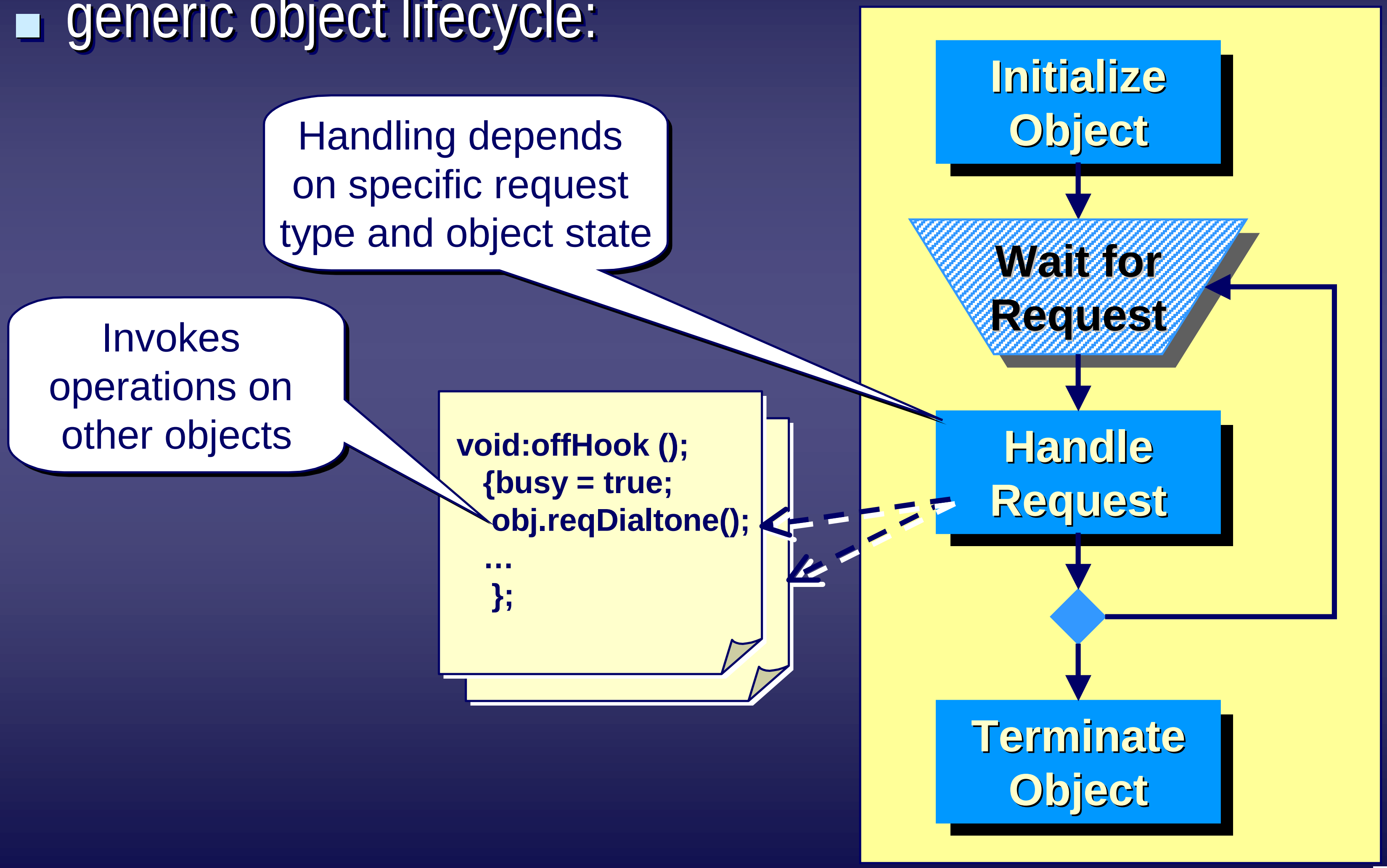
Telephone Call Object

abortCall ()
addParty (t:Telephone)
reportDuration ()

The object paradigm allows us to create our own (virtual) reality!

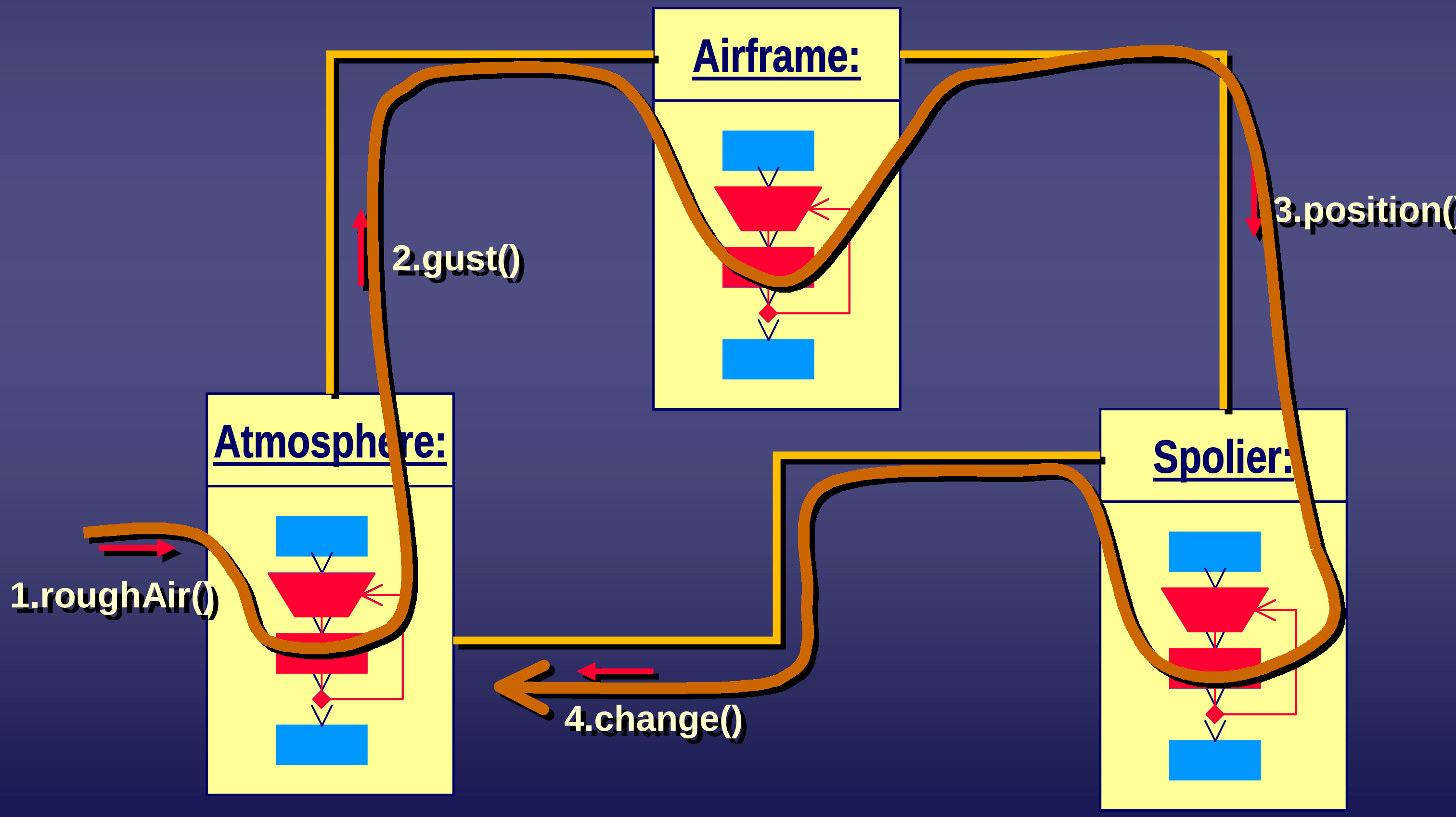
Object Behavior

- In essence, an object is a *server*
  - generic object lifecycle:



Making Things Happen with Objects

- Higher-level behavior “emerges” through the interactions of individual objects

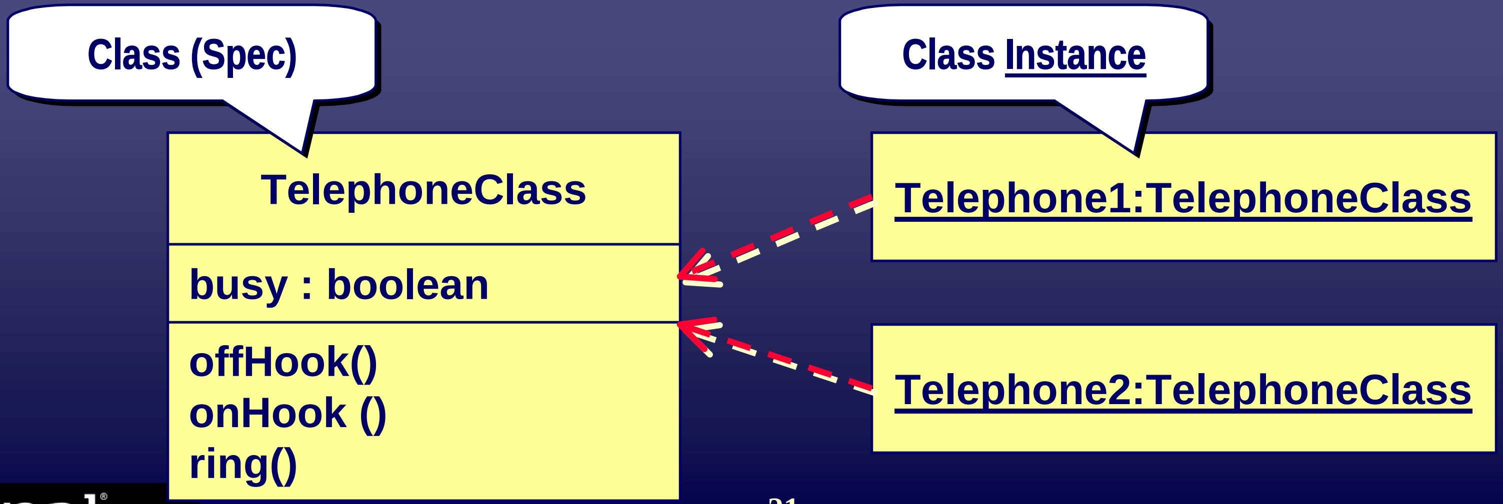


Objects and Emergent Behavior

- One of the main problems of many current OO programming languages is that they do not provide a means for specifying high-level emergent behavior
  - “keyhole” view of high-level behavior
  - difficult to ensure desired high-level behavior will necessarily emerge
- A conflict between top-down and bottom-up design approaches
  - re-usable component programming style defines objects independently of the sequences in which they may participate

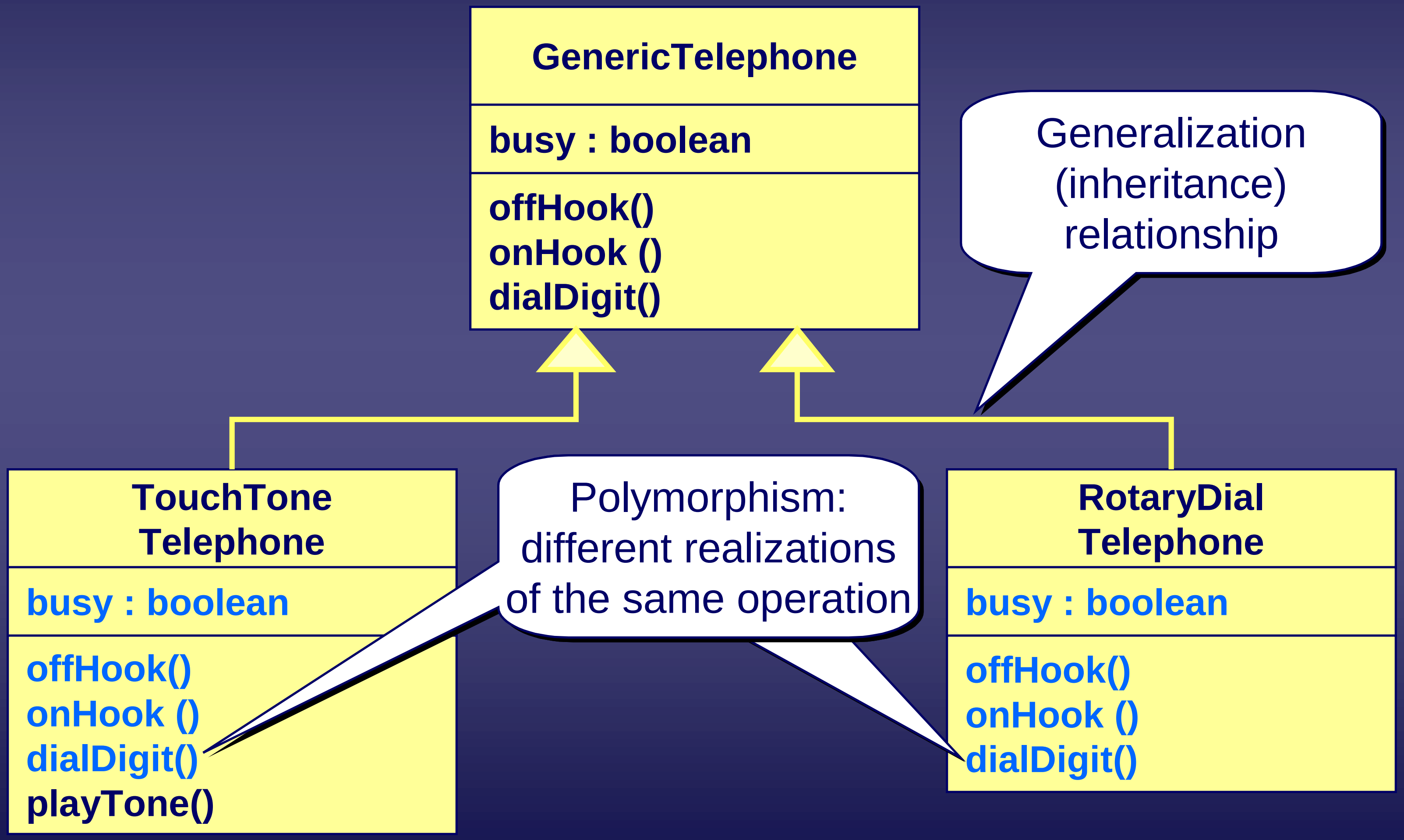
Classes and Instances

- More than one object can be constructed from the same specification–the class
  - A design environment concept
- Objects created from some class specification are called instances of that class
  - A run-time concept



Inheritance and Polymorphism

- A generalization and re-use mechanism



Objects: Summary

- The object paradigm is very well adapted to real-time software systems because of its powerful structural modeling capability
  - networks of collaborating objects
- In addition, the object paradigm comes packaged with a number of well-established techniques:
  - modularity
  - information hiding
  - generalization/refinement mechanisms (e.g., inheritance)
  - genericity

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The Unified Modeling Language

- A consolidation of proven ideas and practices based on the object paradigm into a general-purpose OO modeling language
  - Inititated by Rational Software (Booch, Rumbaugh, Jacobson)
- Standardized by the Object Management Group in 1997
- Major advantages:
  - widely adopted by software practitioners
  - widely taught in universities and technical seminars
  - supported by many software tool vendors

Evolution of UML

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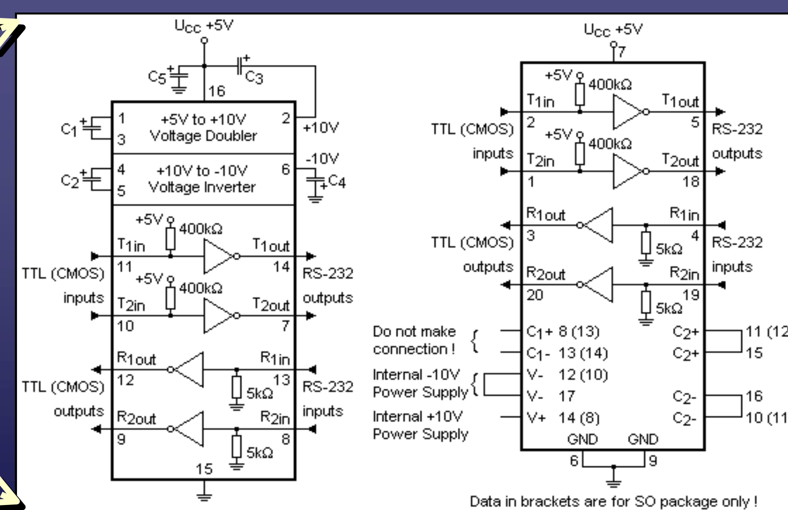
Components of UML

- Basic set of (extensible) modeling concepts
  - used for modeling both problems and solutions (object, class, association)
  - deep semantic roots
- Formal rules of semantically meaningful composition (well-formedness)
- Graphical notation for modeling concepts
  - 8 different diagram types (requirements, structure, behavior, deployment)

Introducing Views and Viewpoints

- *Viewpoint:* a set of related concerns regarding some system
- *View:* a <u>model</u> of a system based on a particular viewpoint
  - abstracts out detail that is irrelevant for that set of concerns

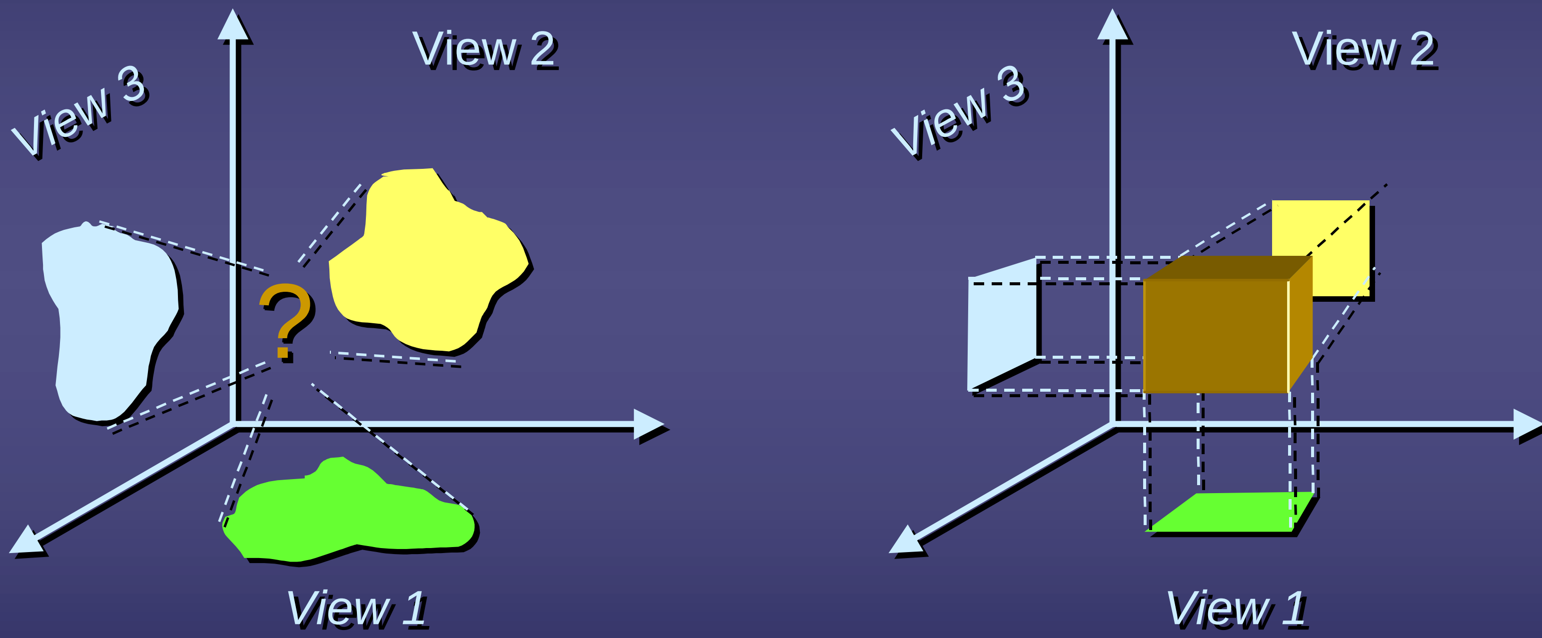
Radio: Designer view



Radio: Radio: user view

Model-Based and View-Based Approaches

- UML uses a model-based approach rather than a view-based approach



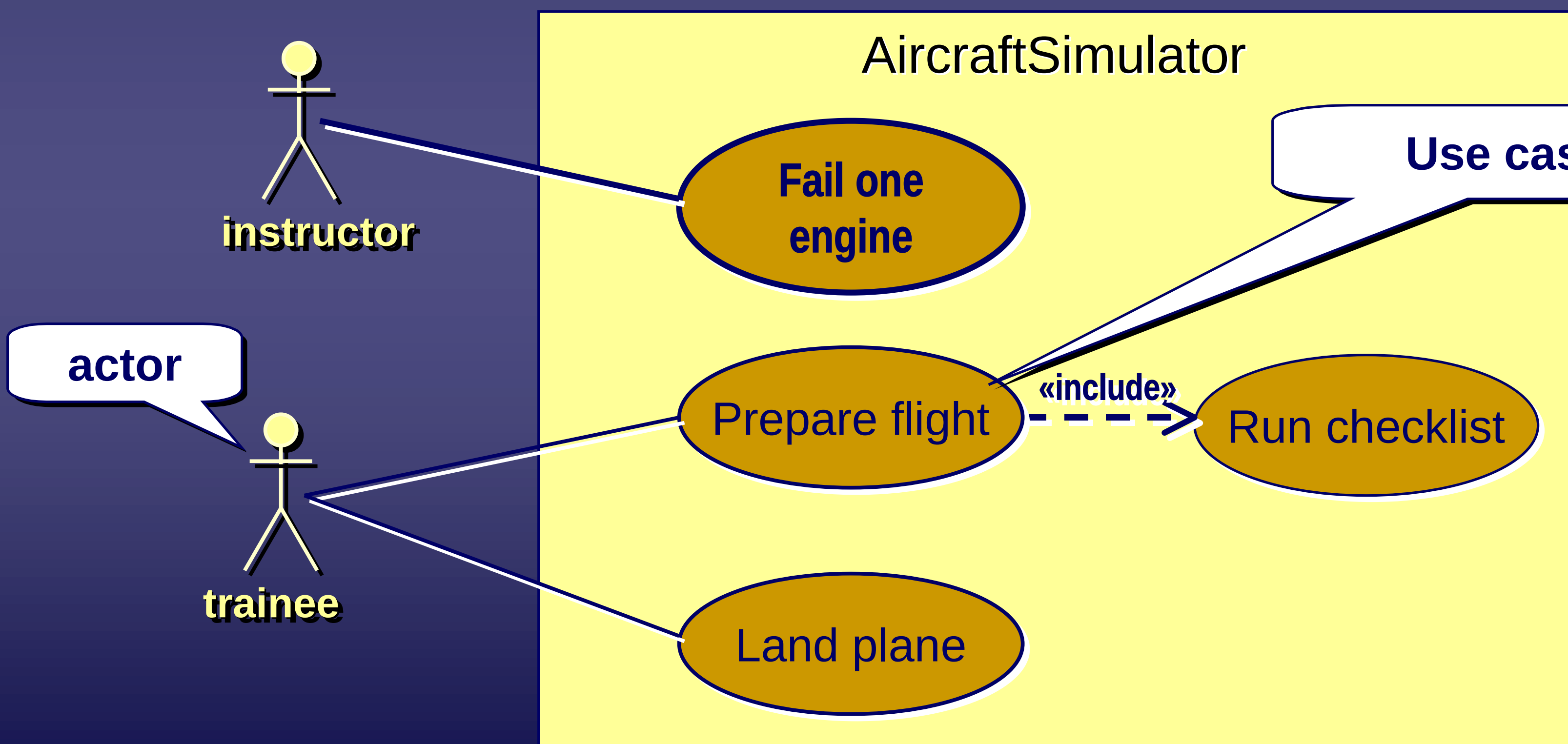
Model-view consistency is enforced through the UML metamodel

UML Model Views

- Requirements (use case diagrams)
- Static structure (class diagrams)
  - kinds of objects and their relationships
- Object behavior (state machines)
  - possible life histories of an object
- Inter-object behavior (activity, sequence, and collaboration diagrams)
  - flow of control among objects to achieve system-level behavior
- Physical implementation structures (component and deployment diagrams)
  - software modules and deployment on physical nodes

Use Case Diagrams

- Used to capture functional requirements
  - useful as principal drivers of the overall development process

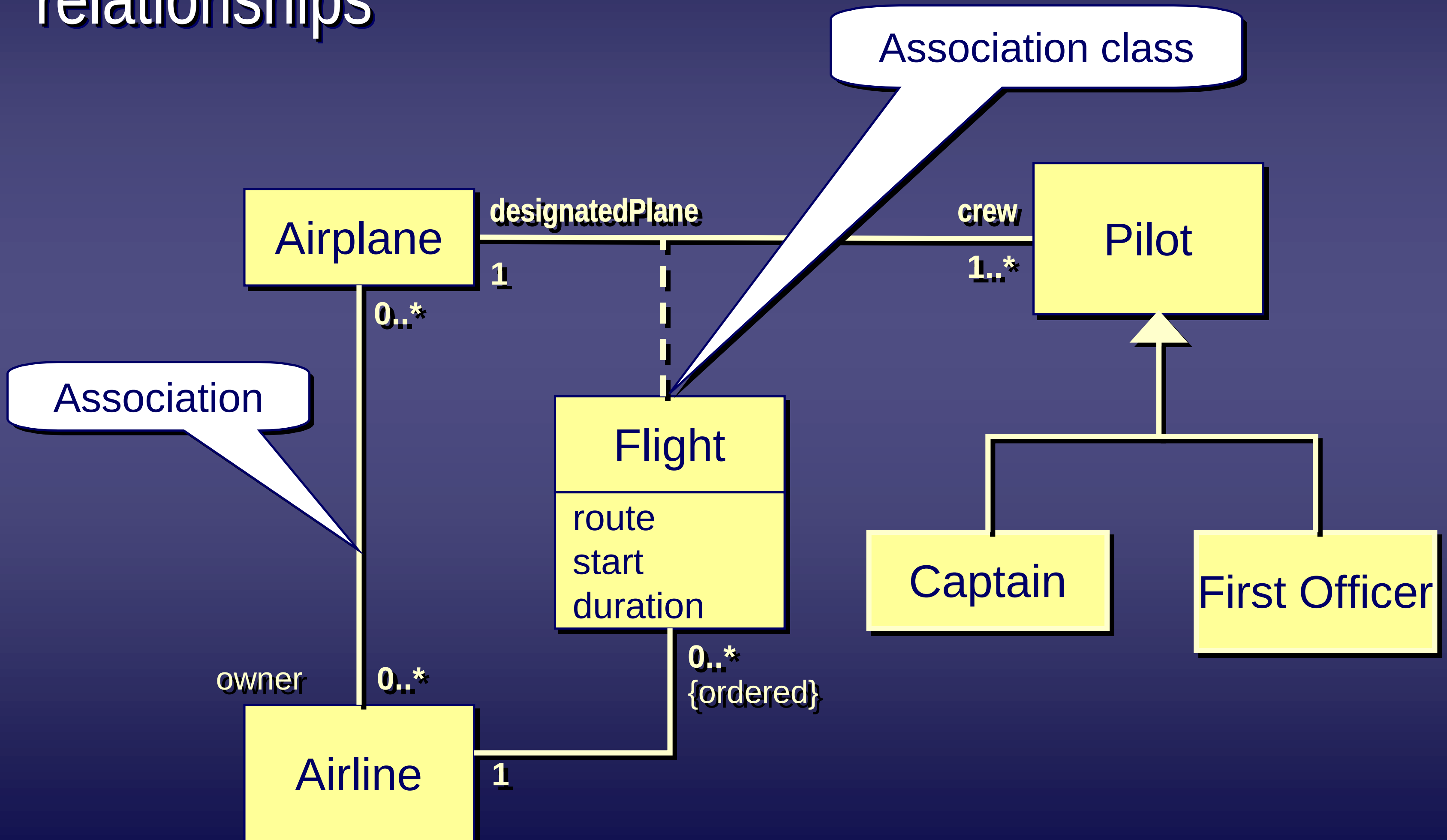


Use Cases and RT Systems

- As useful as in any other domain
  - fundamental drivers of definition, development, and testing
- However….
  - Focus on function (functional requirements)
  - In RT systems, much focus on non-functional requirements
    - e.g., end-to-end delays, maximum response times,…
  - No standard way of associating such non-functional requirements with use cases
  - Use cases do not deal with many important "ilities" (availability, reliability, maintainability,…) that are critical in many real-time systems

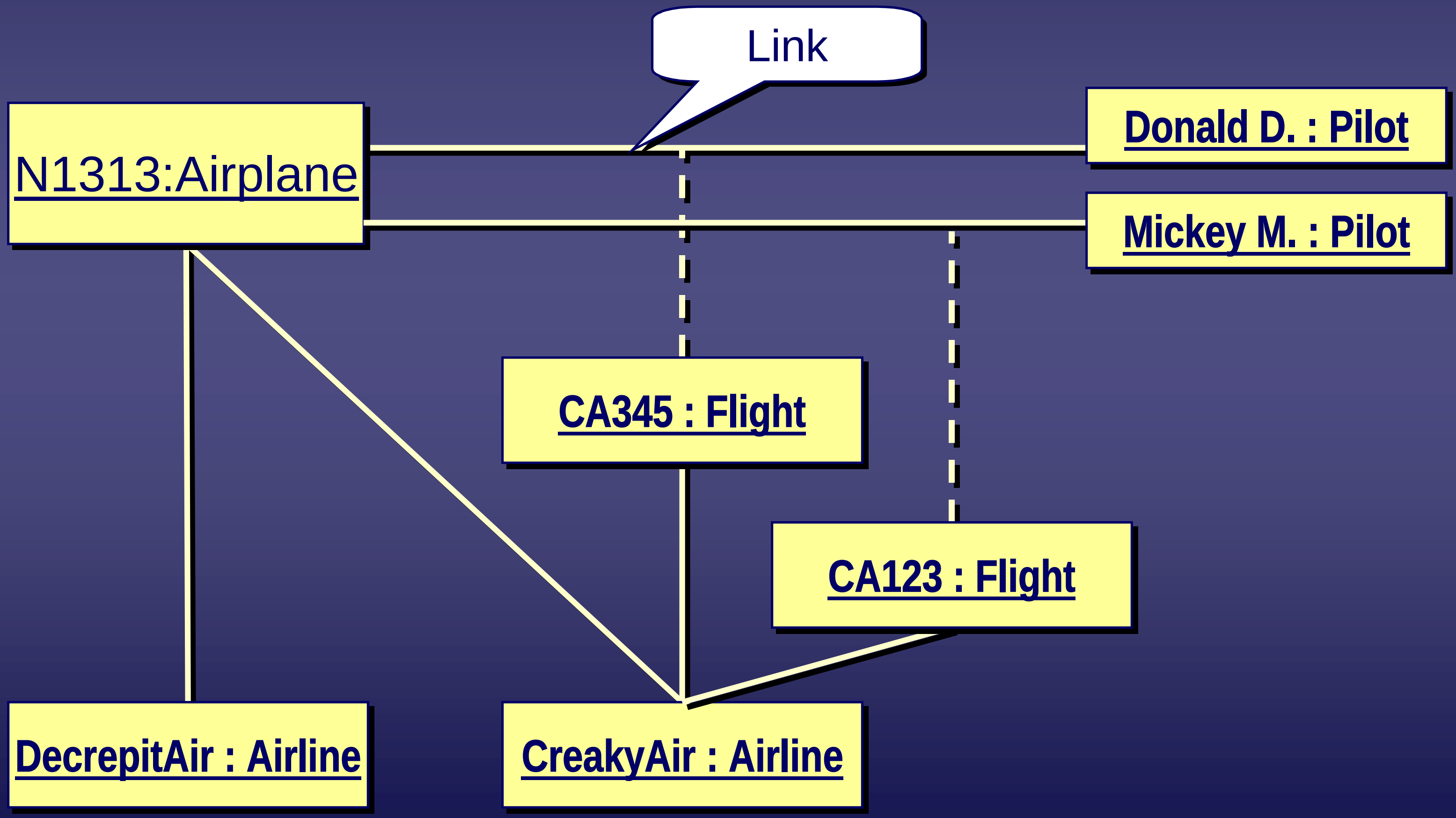
Class Diagram

- Shows the entities in a system and their general relationships



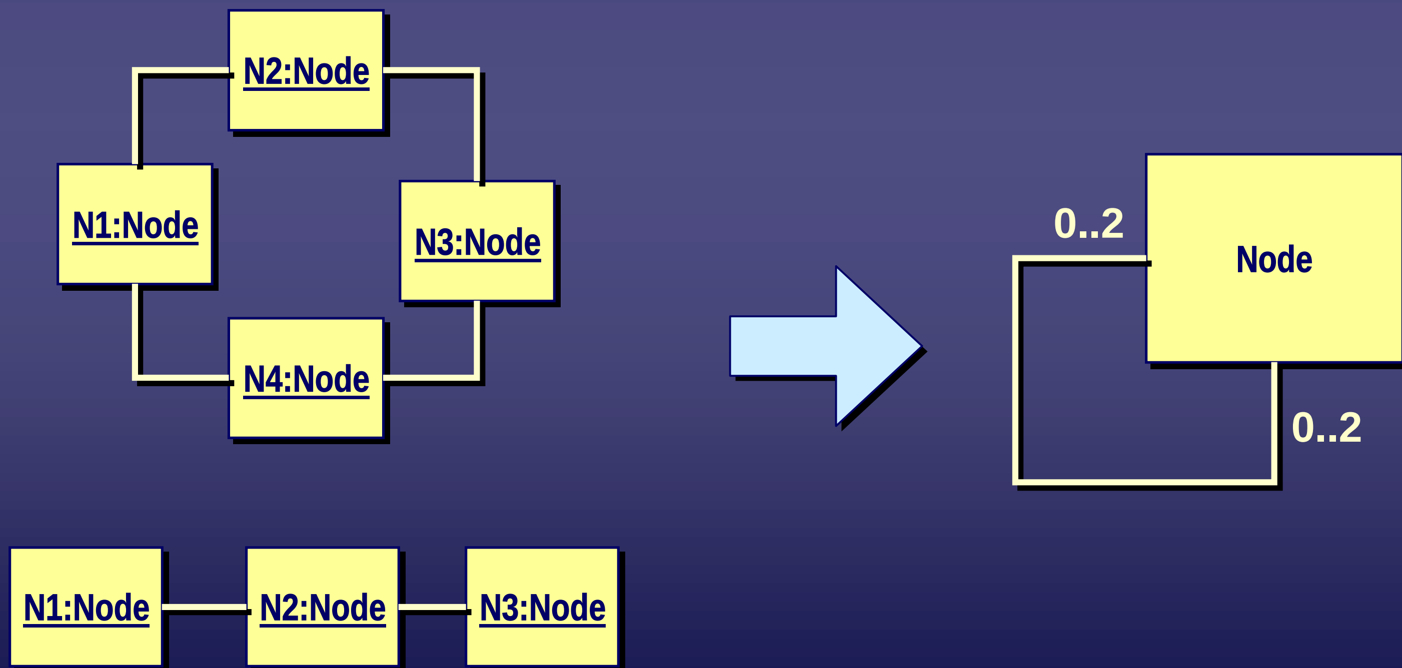
Object Instance Diagram

- Shows object instances in a particular case



Class Diagrams and RT Systems

- Class diagrams are very abstract and sometimes leave out crucial system information (e.g., topology)
  - e.g., common class diagram for both systems

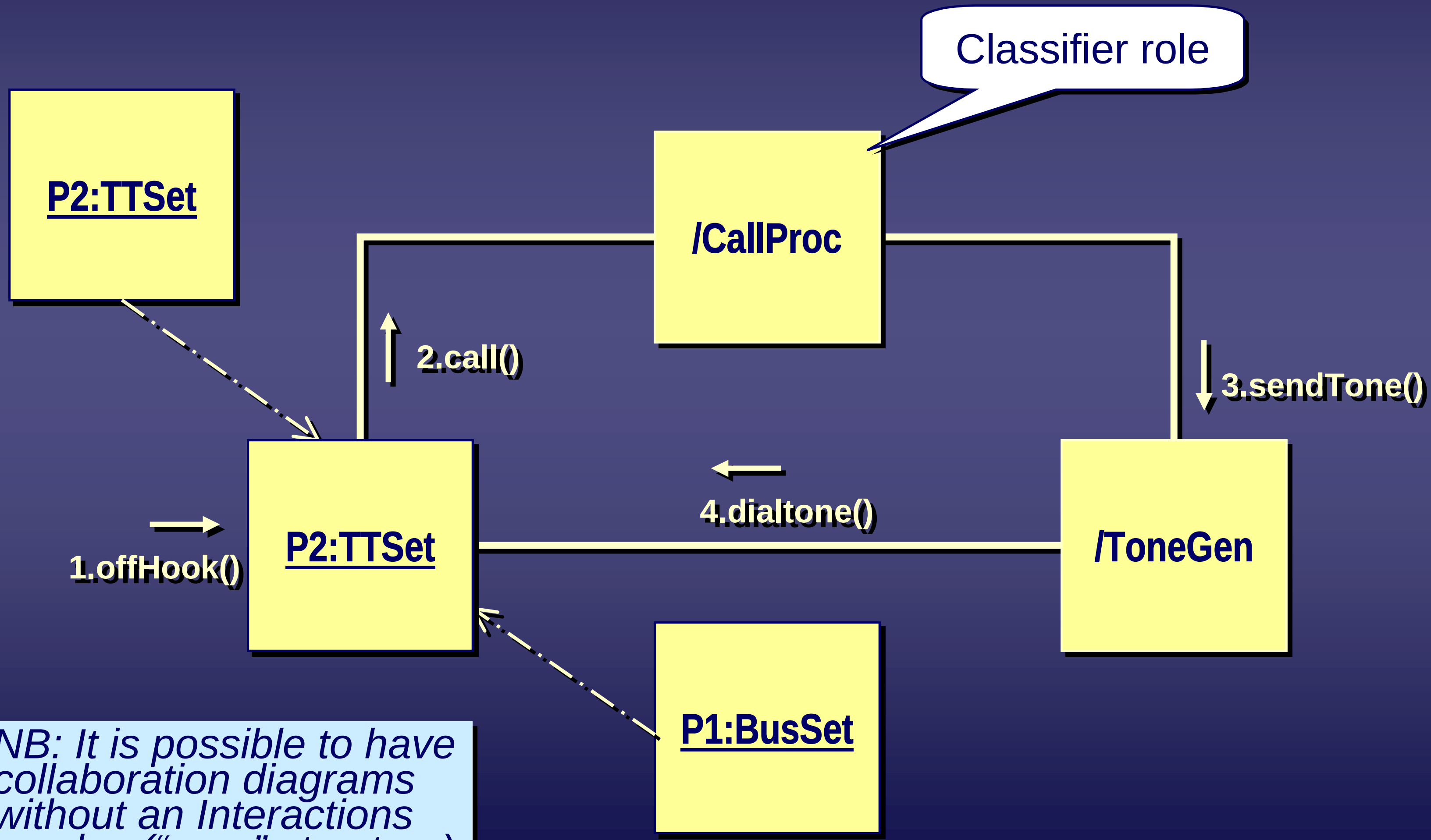


Object Diagrams to the Rescue?

- Object (instance) diagrams do show topologies
- However…
  - in principle, object diagrams only represent “snapshots” of a system at a particular point in time
  - no guarantee that they hold throughout the lifetime of the system
  - need “prototypical” object diagrams
  - but, such semantics are not defined in the current standard

Collaboration Diagram

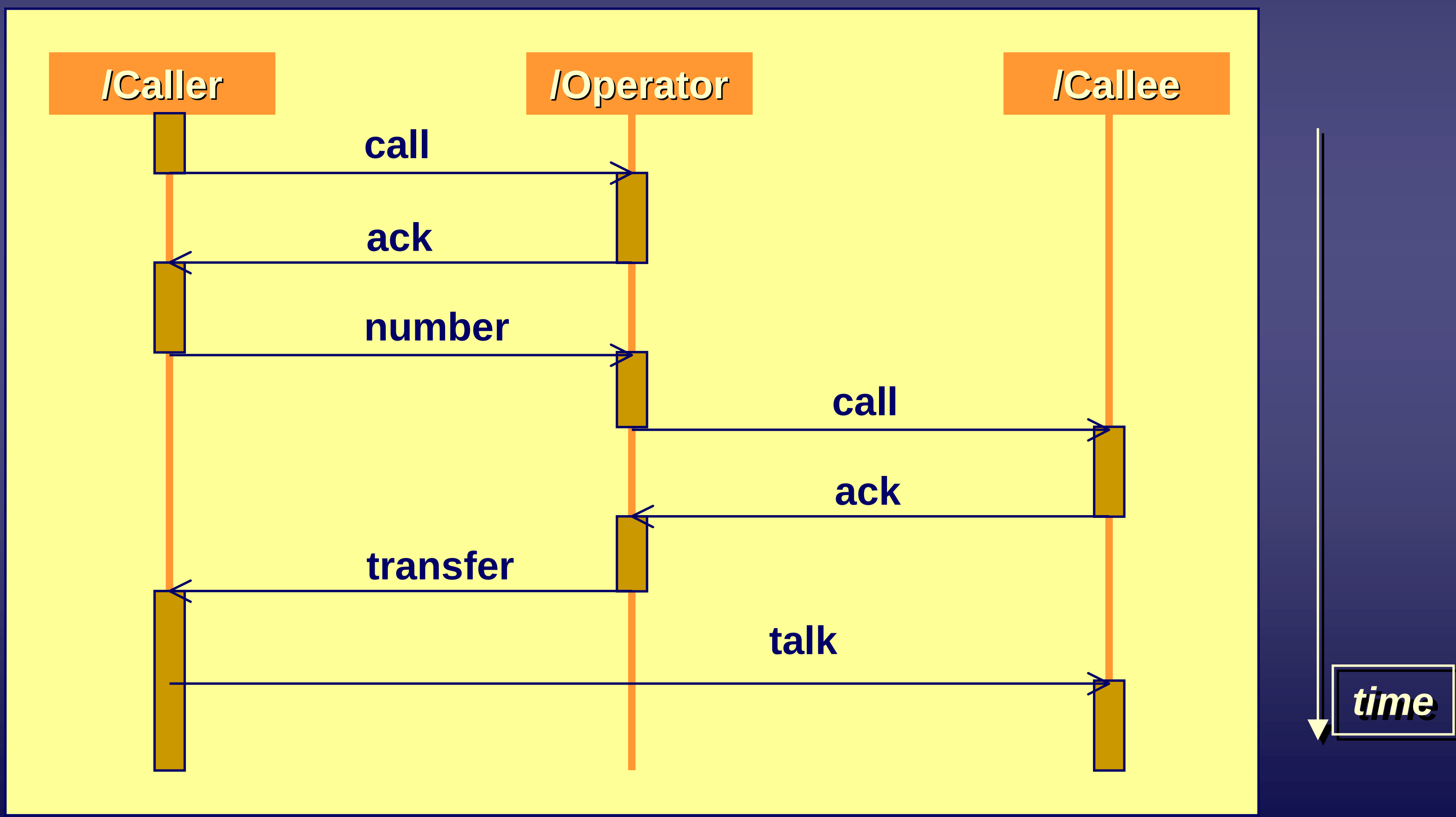
- Depict generic structural and behavioral patterns



NB: It is possible to have collaboration diagrams without an Interactions overlay ("pure" structure)

Sequence Diagrams

- Show interactions between objects with a focus on communications (a different representation of a collaboration)

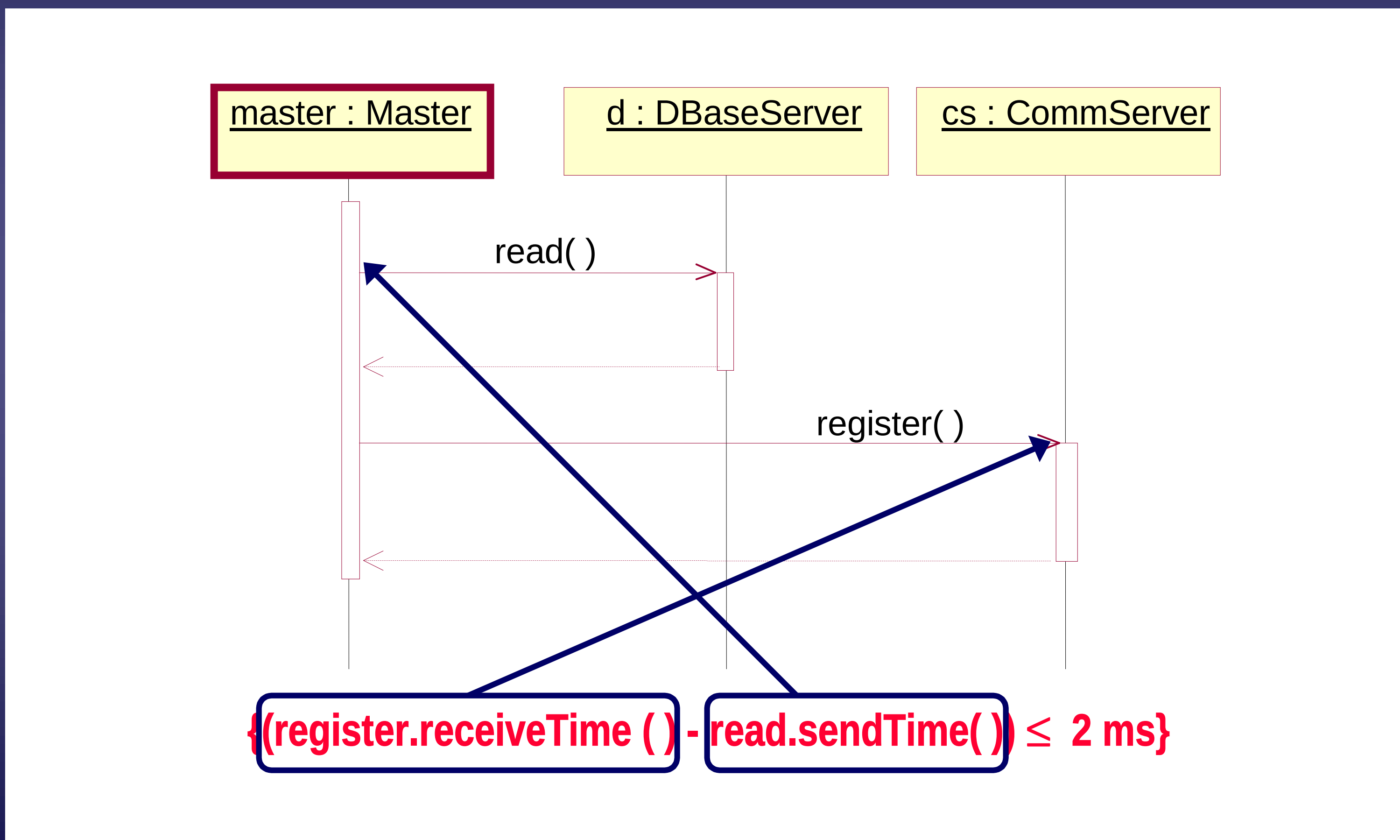


Sequence Diagrams and RT Systems

- Sequence diagrams are extremely useful for showing object interactions
  - very common in many real-time systems
  - well suited for event-driven behavior
  - in telecom, many protocol standards are defined using sequence diagrams
- However…
  - No standard way of denoting timing information
  - UML sequence diagrams do not scale up very well for modeling large systems with complex sequences

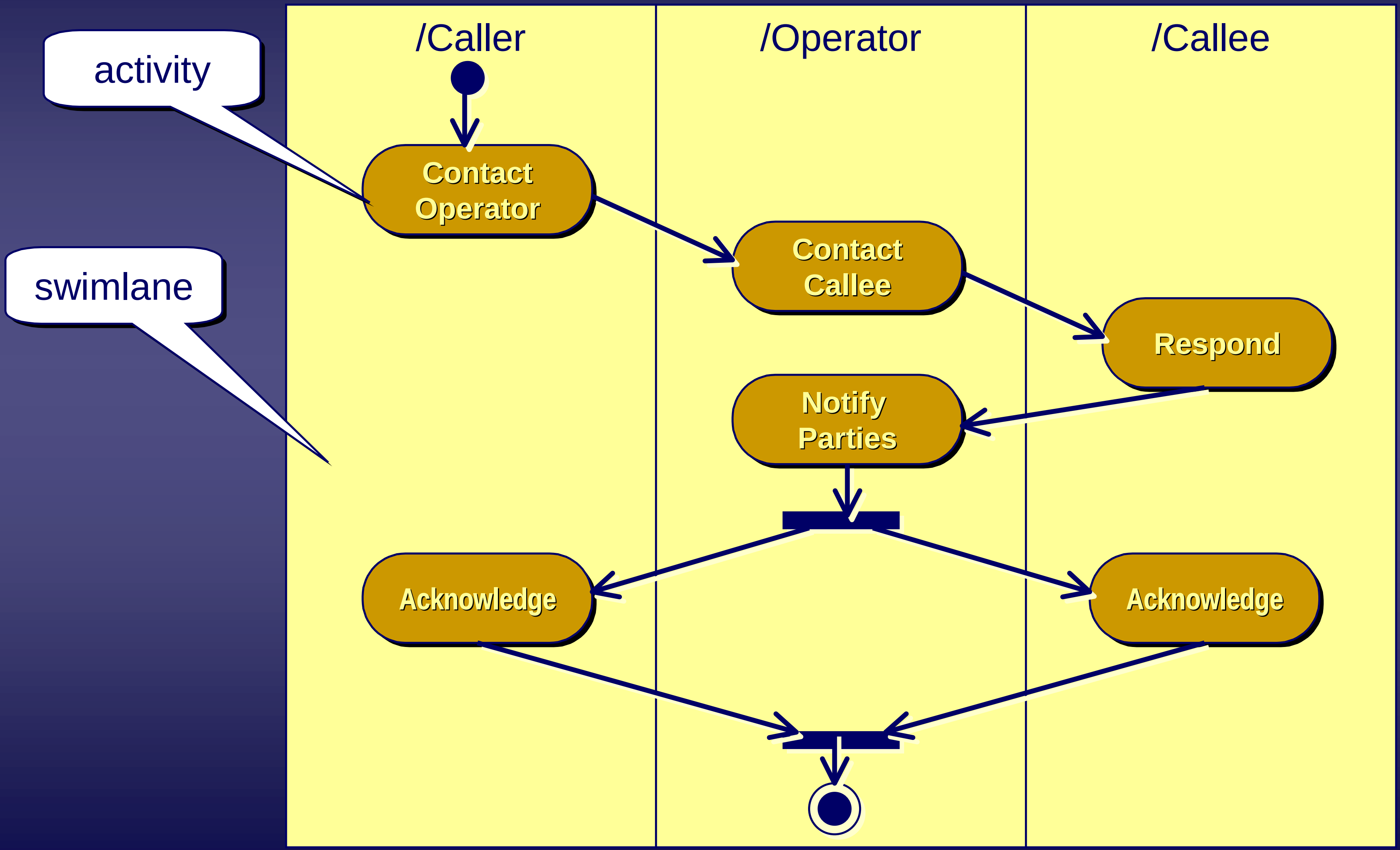
Using Timing Marks with Sequence Diagrams

- Specifying constraints



Activity Diagrams

- Different focus compared to sequence diagrams



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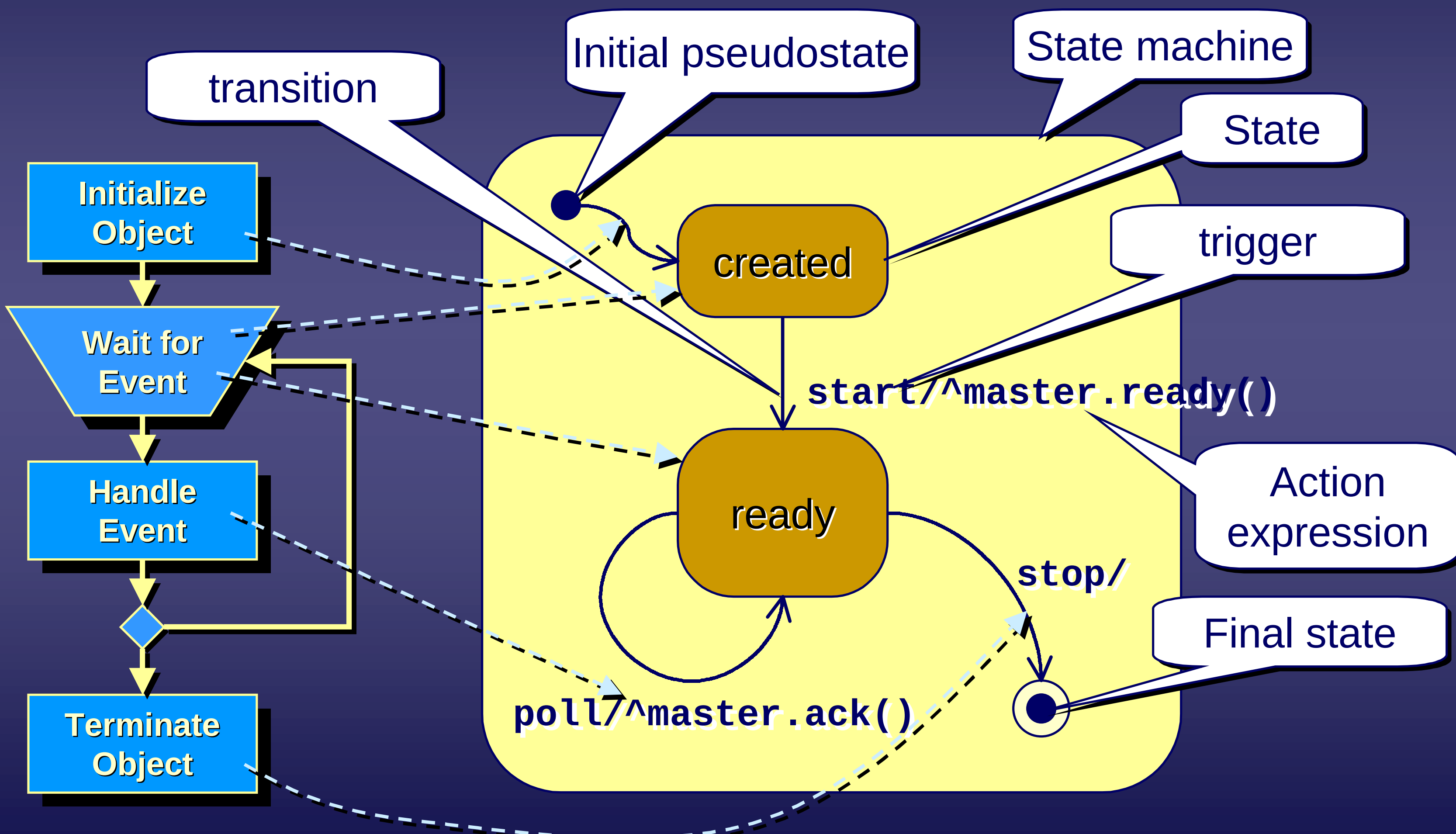
Activity Diagrams and RT Systems

- Better than sequence diagrams for
  - showing concurrency (forks and joins are explicit)
  - scaling up to complex systems
- However…
  - No standard way of denoting timing information
  - Less well-suited for describing event-driven behavior

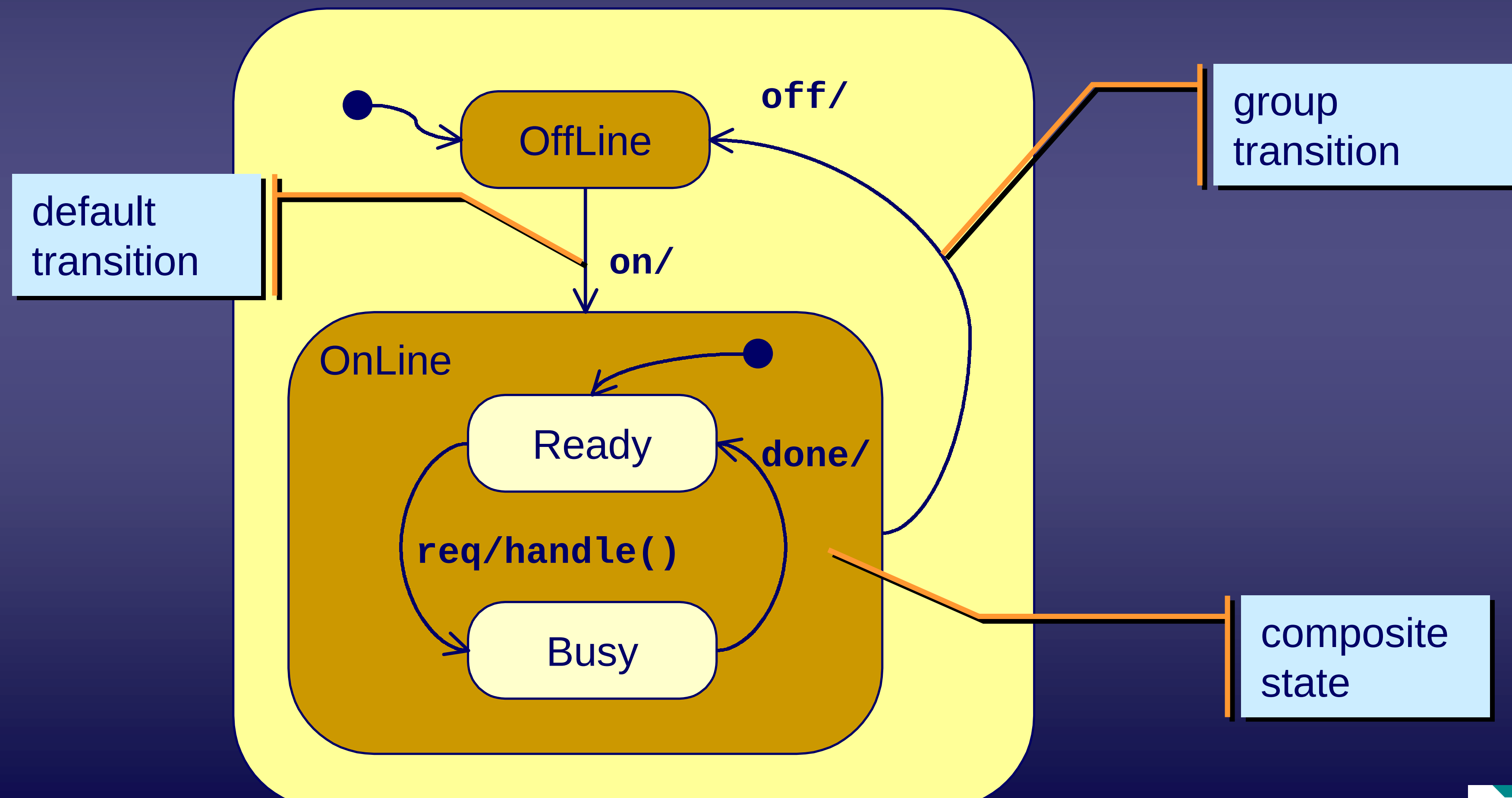
State Machine Diagram

- Each state corresponds to a selective receive action



Hierarchical States and Transitions

- Allows step-wise refinement and viewing of complex behavior



State Machines and RT Systems

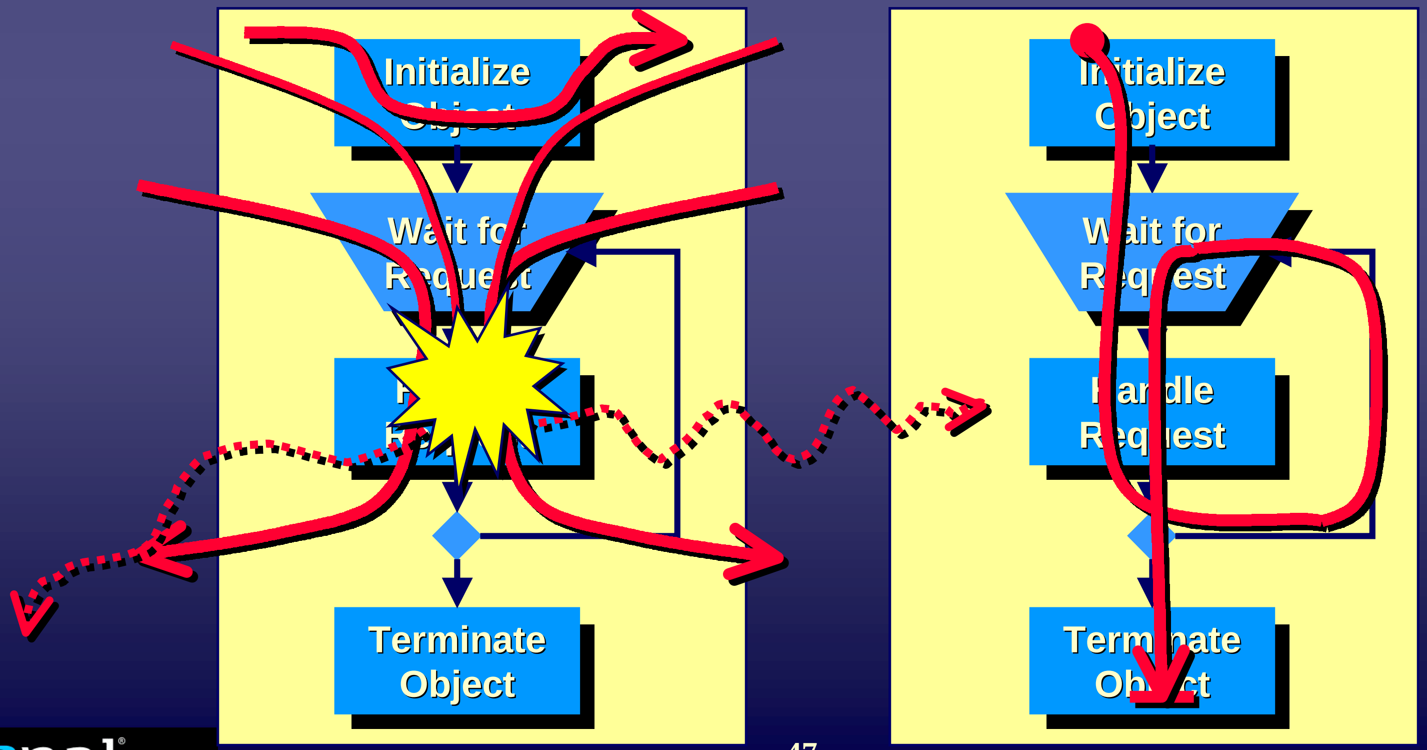
- Many real-time systems are event-driven
  - very well suited to those systems
  - scale up very nicely
- However…
  - not directly connected to time (except for time events)
  - e.g., run-to-completion paradigm

Implementing Time-Triggered Systems

- Periodic timers:
  - once initiated they repeatedly send TimeEvents at the appropriate intervals until explicitly stopped or cancelled
- In "steady-state" mode, active objects stimulated exclusively by periodic timers become periodic tasks
  - allows rate-monotonic scheduling policies
  - schedulers use the priorities of periodic timers to make scheduling decisions

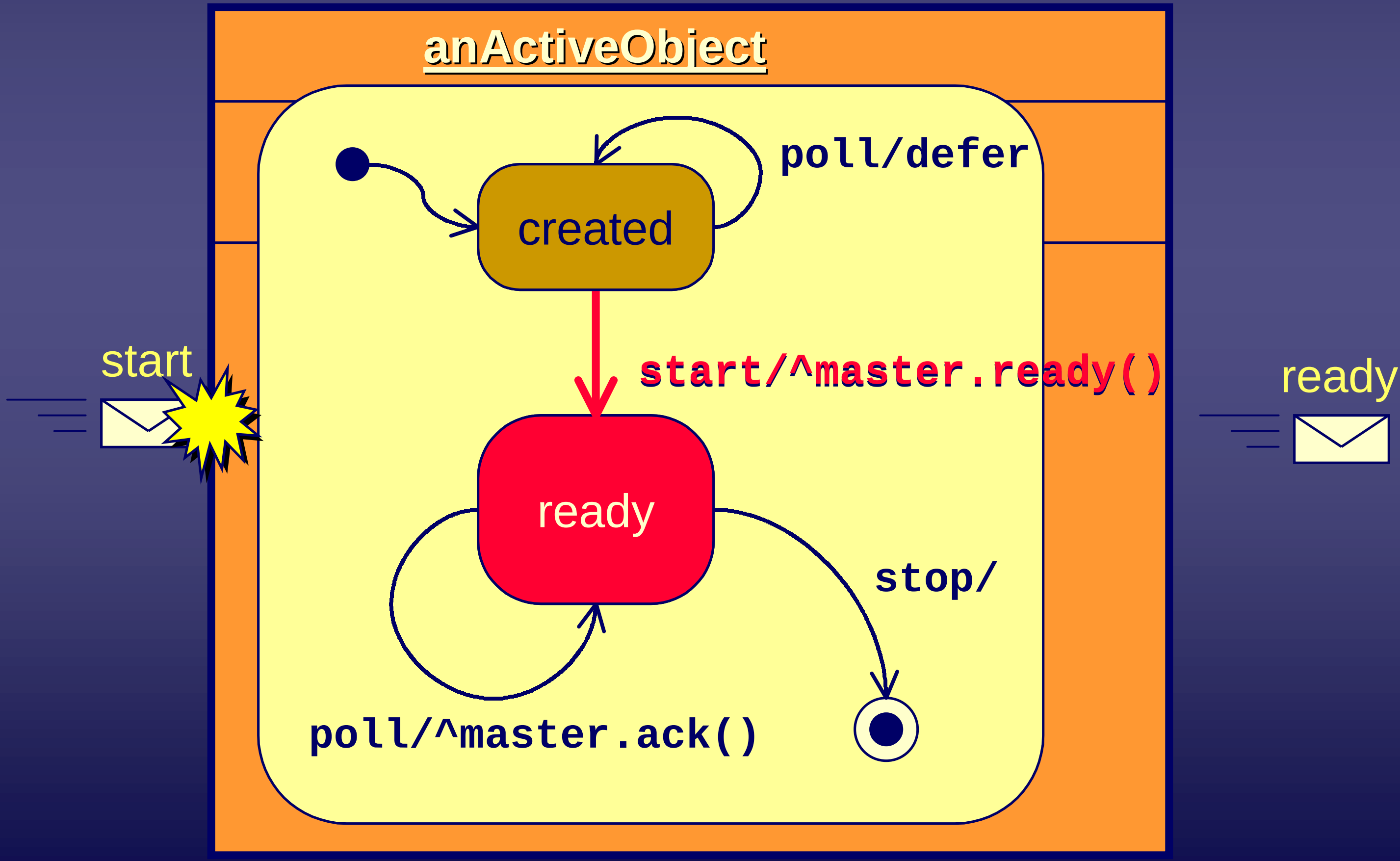
Objects and Concurrency

- *Passive objects:* have no control of their communications
  - Clients determine when to invoke an operation
- *Active objects:* can control when to respond to requests
  - Can avoid concurrency conflicts
  - Require at least one independent engineering-level thread



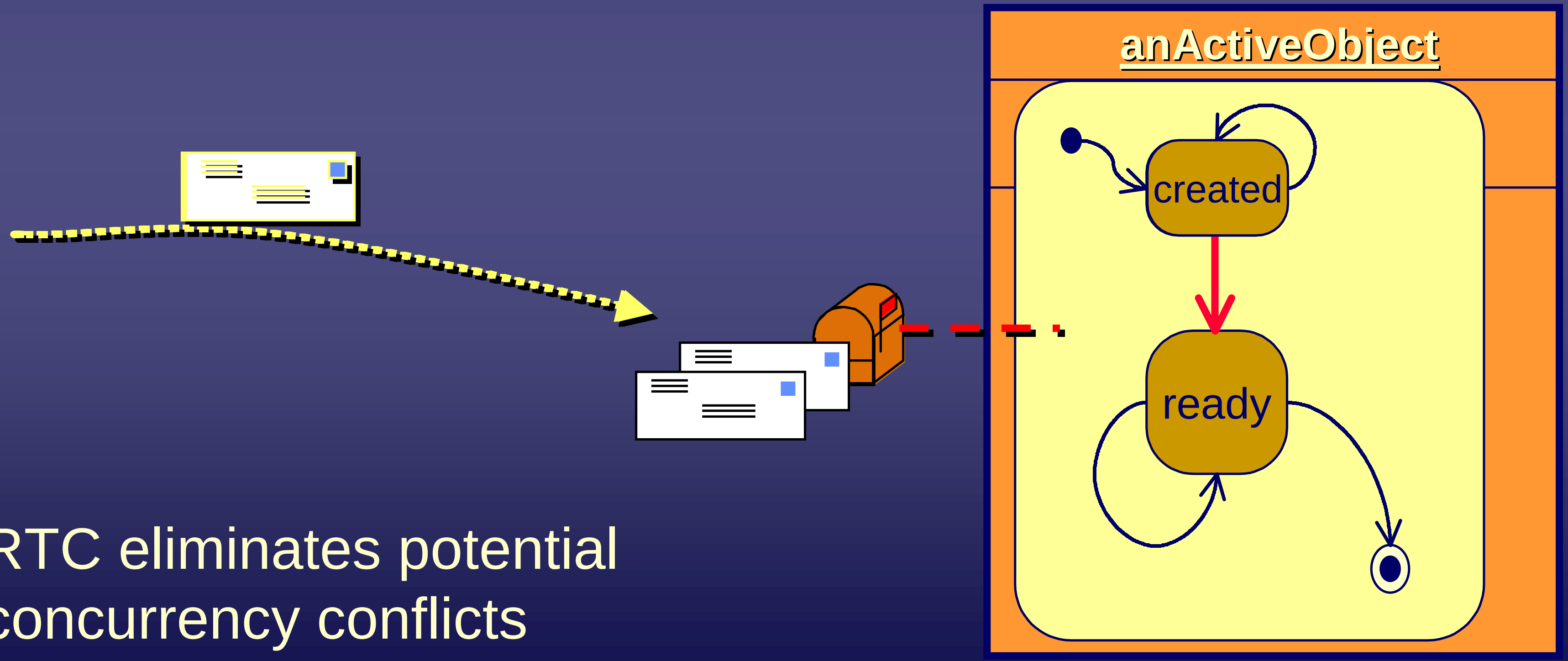
The Active Objects of UML

- Single thread of execution
- Behavior defined by state machines (event driven)



Active Object Semantics

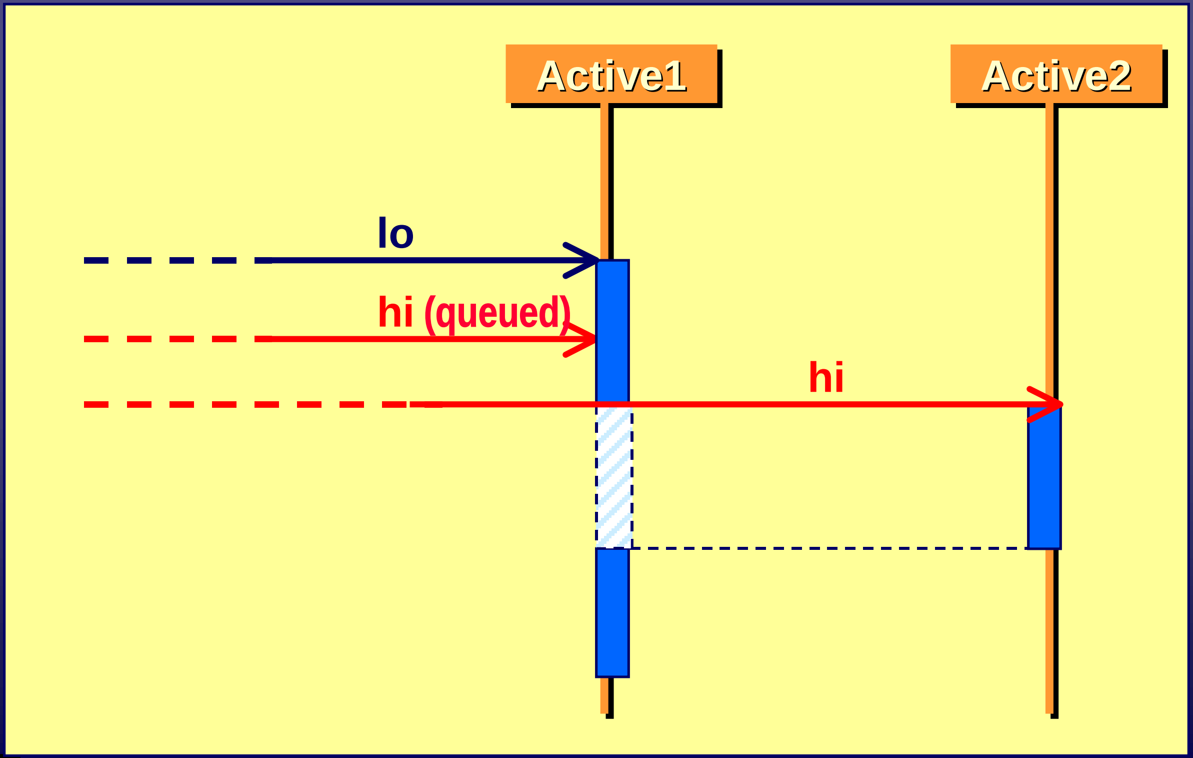
- Concurrent incoming events are queued and handled one-at-a-time regardless of priority
- *run-to-completion* (RTC) execution model



RTC eliminates potential concurrency conflicts

RTC Semantics

- A high priority event for another active object will preempt an active object on the same processor that is handling a low-priority event
  - Limited priority inversion can occur

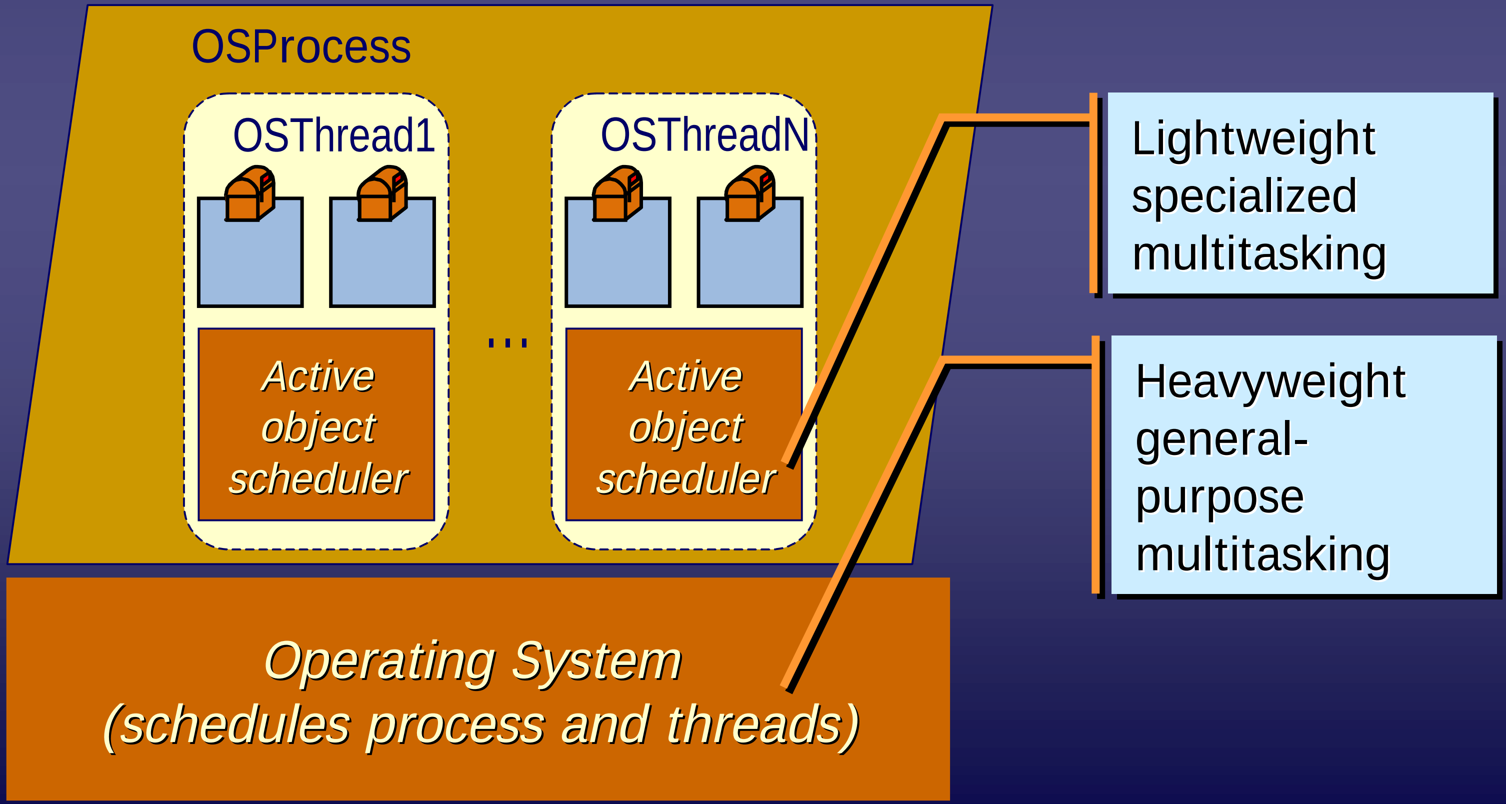


RTC Analysis

- Advantages:
  - Eliminates concurrency conflicts for all passive objects encapsulated by active objects
  - No explicit synchronization code required
  - Low-overhead context switching (RTC implies that stack does not need to be preserved)
- Disadvantage:
  - Limited priority inversion can occur (higher priority activity may have to wait for a lower-priority activity to complete)
  - Can be circumvented but at the expense of application-level complexity

Example: Active Objects

- Active object ≠ OS thread
  - two-tier scheduling scheme
  - event priorities vs thread priorities



UML Concurrency Model and RT Systems

- Active objects are the major concurrency mechanism of UML
  - automatically resolve certain concurrency conflicts
- However...
  - The priority inversion inherent in RTC may be unacceptable in some cases
  - How does this map to concurrency mechanisms that are used in the real-time domain (processes, threads, semaphores, real-time scheduling methods, etc.)?
  - No clear way of exploiting real-time analyses methods (e.g., schedulability analysis)

Scheduling in UML

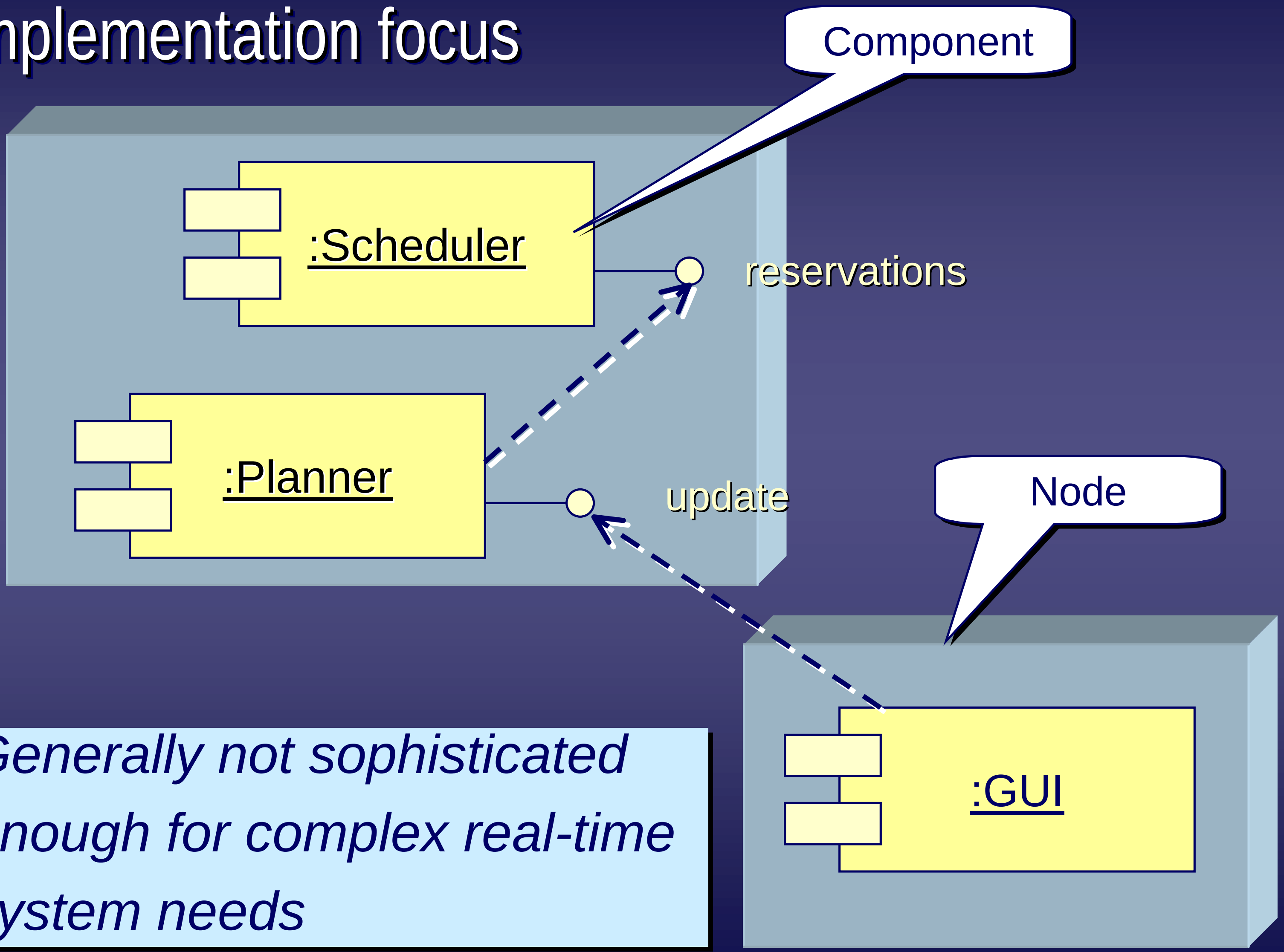
- Scheduling approach undefined
  - Hints of event-based priorities (versus thread-based)
  - Timing events allow realization of time-triggered systems
- The actual scheduling policy is unspecified
  - A *semantic variation point*
  - Can be customized to suit application requirements

The Model of Time in UML

- Unbiased and uncommitted (i.e., it does not exist):
  - Time data type declared but not defined (could be either continuous or discrete)
  - No built-in assumptions about global time source (open to modeling distributed systems)
- Related concepts:
  - Time events: generated by the occurrence of a specific instant
  - Assumes some kind of run-time Timing Service

Component and Deployment Diagrams

- Implementation focus



Generally not sophisticated enough for complex real-time system needs

Implementation Diagrams and RT Systems

- Probably the weakest part of UML
- Not sophisticated enough to capture the various complex aspects of deployment common to real-time systems
  - deferred mapping of software to hardware
  - mapping of software to software
- No standard way to describe the quantitative requirements/characteristics of hardware and software (e.g., scheduling discipline)
- …..

UML Summary

- An industry standard for analysis and design of object-oriented systems
  - based on extensive experience and best practices
  - gaining rapid acceptance (training, tools, books)
- Comprises:
  - set of modeling concepts
  - a standard graphical notation
- Represented through 8 different diagram types
  - class, state machine, collaboration, use case, sequence, activity, component, deployment

UML and RT Systems Summary

- Using UML for real-time systems automatically brings the benefits of the object paradigm
  - structural focus, inheritance, strong encapsulation, polymorphism,…
- However, there are many open questions
  - best ways of using UML in the real-time domain
  - missing or non-standard concepts
  - ability to create predictive models for real time

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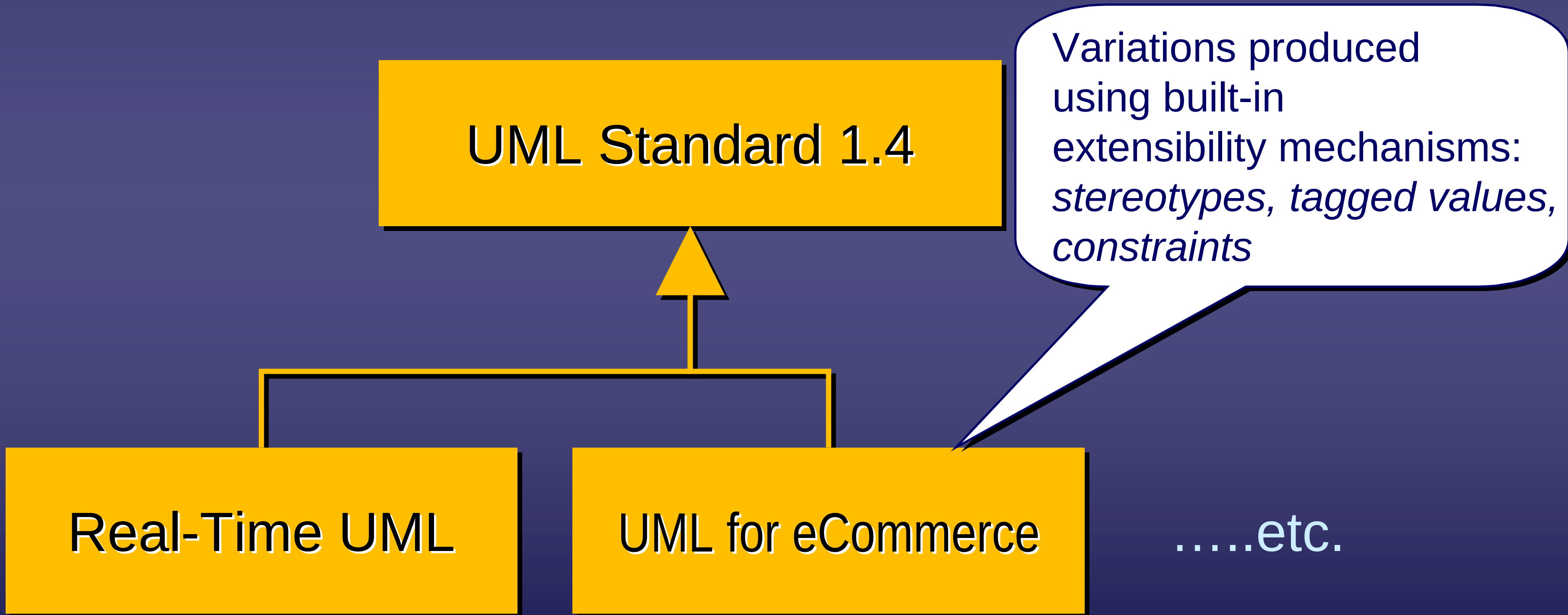
Semantic Variation in UML

- Semantic aspects that are:
  - undefined (e.g., scheduling discipline), or
  - intentionally ambiguous (multiple, mutually-exclusive, interpretations)
- Why?
  - Different domains require different specializations
  - The applicability and usefulness of UML would have been severely constrained if it could not support such diversity
- The scope and semantic impact of semantic variation choices must be strictly limited

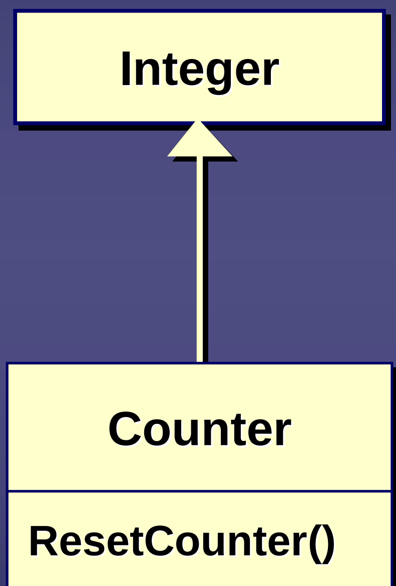
Specialization of UML

- Avoiding the PL/I syndrome (“language bloat”)
  - UML standard as a basis for a “family of languages”



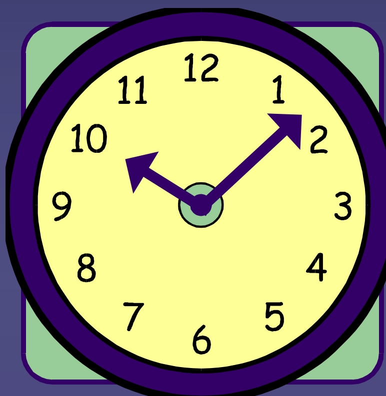
How Do We Specialize UML?

- Typically used to capture semantics that cannot be specified using UML itself



Specialization through regular inheritance

But, how can we specify a clock?

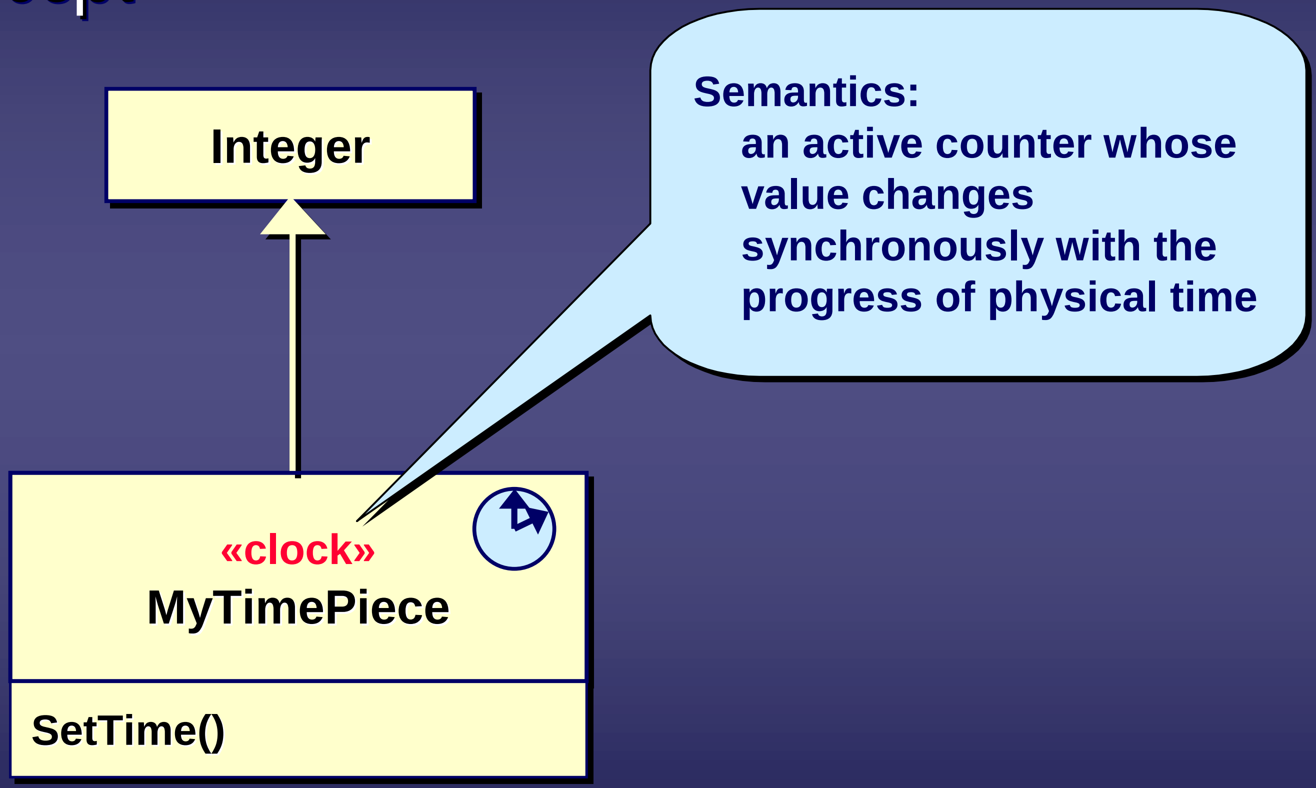


Semantics:

an active counter whose value changes synchronously with the progress of physical time

Stereotyping UML Concepts

- Example: a “clock” stereotype based on the generic UML Class concept



UML Profiles

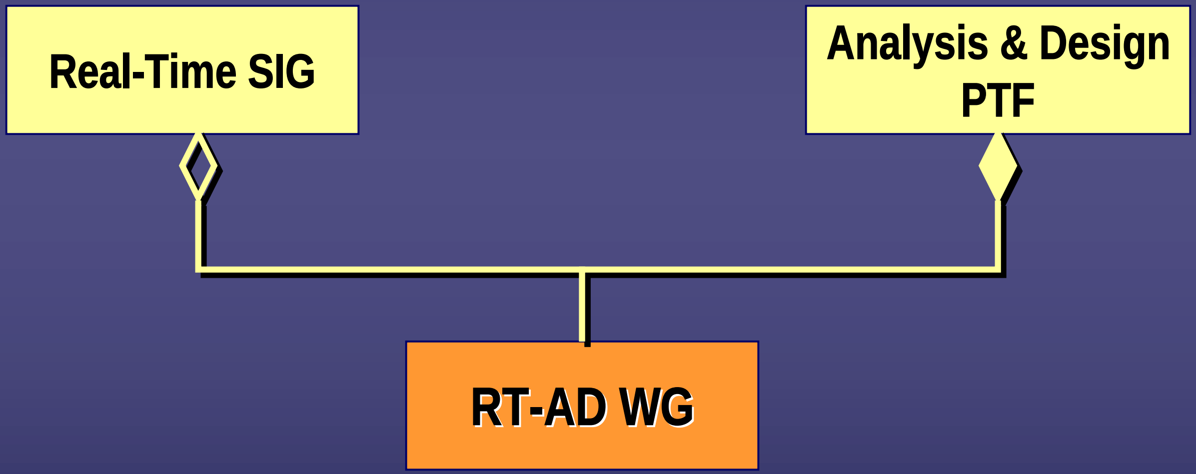
- A package of related specializations of general UML concepts that capture domain-specific variations and usage patterns
  - *A domain-specific interpretation of UML*
- Fully conformant with the UML standard
  - additional semantic constraints cannot contradict the general UML semantics
  - within the “semantic envelope” defined by the standard

UML Extensibility and RT Systems

- The extensibility mechanisms of UML provide an excellent opportunity to fill in the missing bits for real-time applications
- If we can define a standard set of extensions ("real-time profile") then these could provide a common facility for real-time UML modelers and tool builders

Real-Time A&D WG (1 of 2)

- Bridges two domains: modeling and real-time



Real-Time A&D WG (2 of 2)

- Mission:
  - *to investigate and issue requests (RFPs) for standard ways and means to apply UML to real-time problems*
- Three principal areas of investigation:
  - Time-related modeling
  - General quality of service modeling (e.g., availability, reliability, security,…)
  - Real-time system architecture modeling
- Status:
  - first RFP issued (April 1999)
  - second RFP drafted but not submitted

The Real-Time UML RFP

- *“UML profile for scheduling performance and time”*
  - First in a series of real-time specific RFPs (ad/99-03-13)
  - Initial proposal submitted in August 2000 (ad/2000-08-04)
  - Approved by the Analysis & Design Task Force and by the OMG Architecture Board Sept. 2001 (final vote pending)
- Standard methods for UML modeling of:
  - Physical time
  - Timing specifications
  - Timing services and mechanisms
  - Modeling resources (logical and physical)
  - Concurrency and scheduling
  - Software and hardware infrastructure and their mapping
  - ..including specific notations for the above where necessary

Important Caveat

- The RFP does *not* ask for new real-time concepts or methods
- Instead, the intent is to support existing and future modeling techniques and analysis methods in the context of UML
  - ⇒ *response should not be biased towards any particular technique or method*

Response to the RFP

- Just one submission throughout
- Consortium team:
  - ARTiSAN (UML tool vendor)
  - I-Logix (UML tool vendor)
  - Rational (UML tool vendor) - lead
  - Telelogic (UML tool vendor)
  - TimeSys (RT tool and technology vendor)
  - Tri-Pacific Software (RT tool vendor)
- In consultation with many of the top real-time system experts (toolbuilders, analysis technique experts, academics)
  - Prof. Murray Woodside and Prof. Dorina Petriu (Carleton U.) – performance analysis profile

RT Profile: Guiding Principles

- Ability to specify quantitative information directly in UML models
  - key to quantitative analysis and predictive modeling
- Flexibility:
  - users can model their RT systems using modeling approaches and styles of their own choosing
  - open to existing and new analysis techniques
- Facilitate the use of analysis methods
  - eliminate the need for a deep understanding of analysis methods
  - as much as possible, automate the generation of analysis models and the analysis process itself

Quantitative Methods for RT Systems

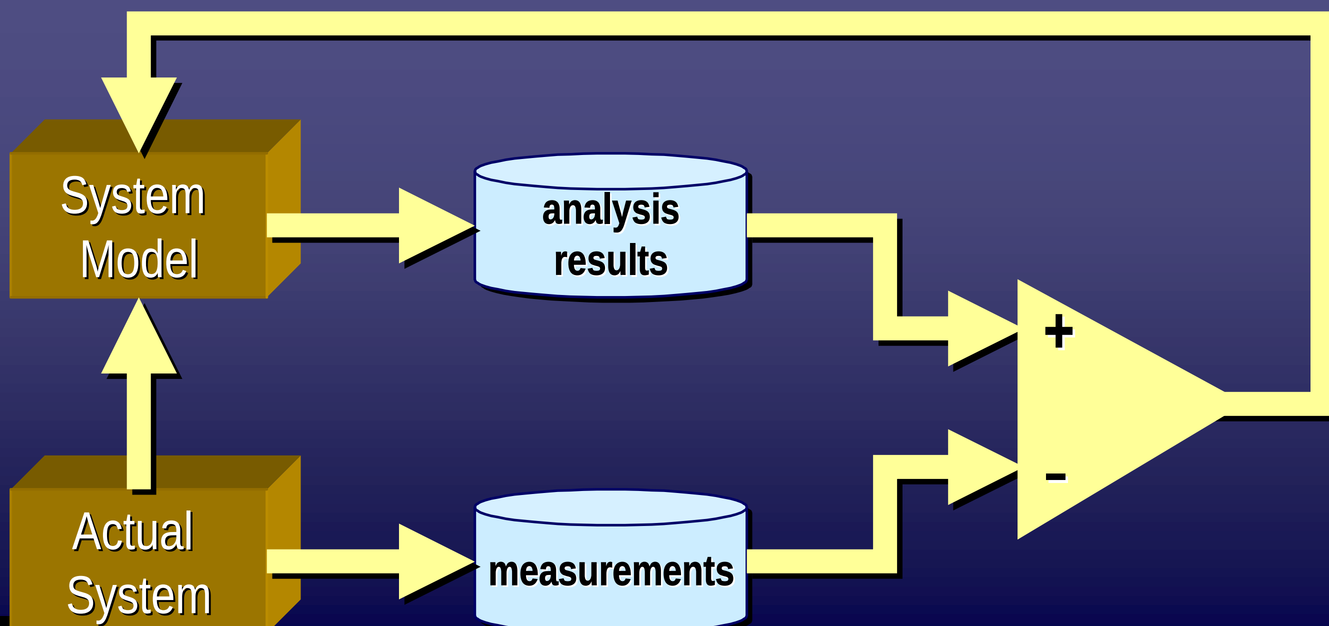
- Once we have included QoS information in our models, we can use *quantitative methods* to:
  - predict system characteristics (detect problems early)
  - analyze existing system
  - synthesize elements of the model
- Methods considered for the profile:
  - Schedulability analysis

    will the system meet all of its deadlines?
  - Performance analysis based on queueing theory

    what kind of response will the system have under load?

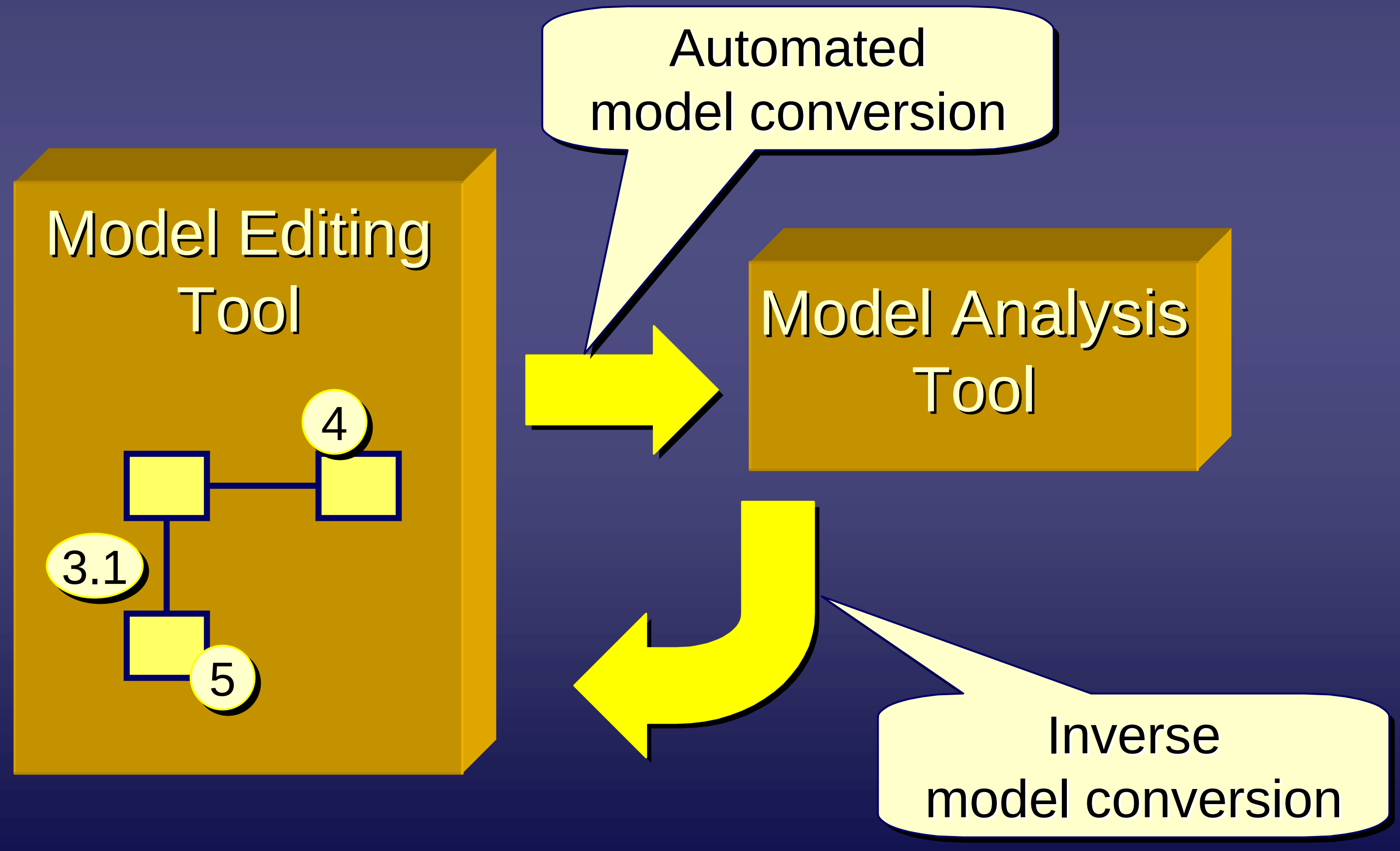
Issues with Quantitative Methods

- Require uncommon and highly-specialized skills
- Software is notoriously difficult to model
  - highly non-linear (detail often matters)
  - models are frequently severely inaccurate and not trustworthy
  - typical modeling process is highly manual:

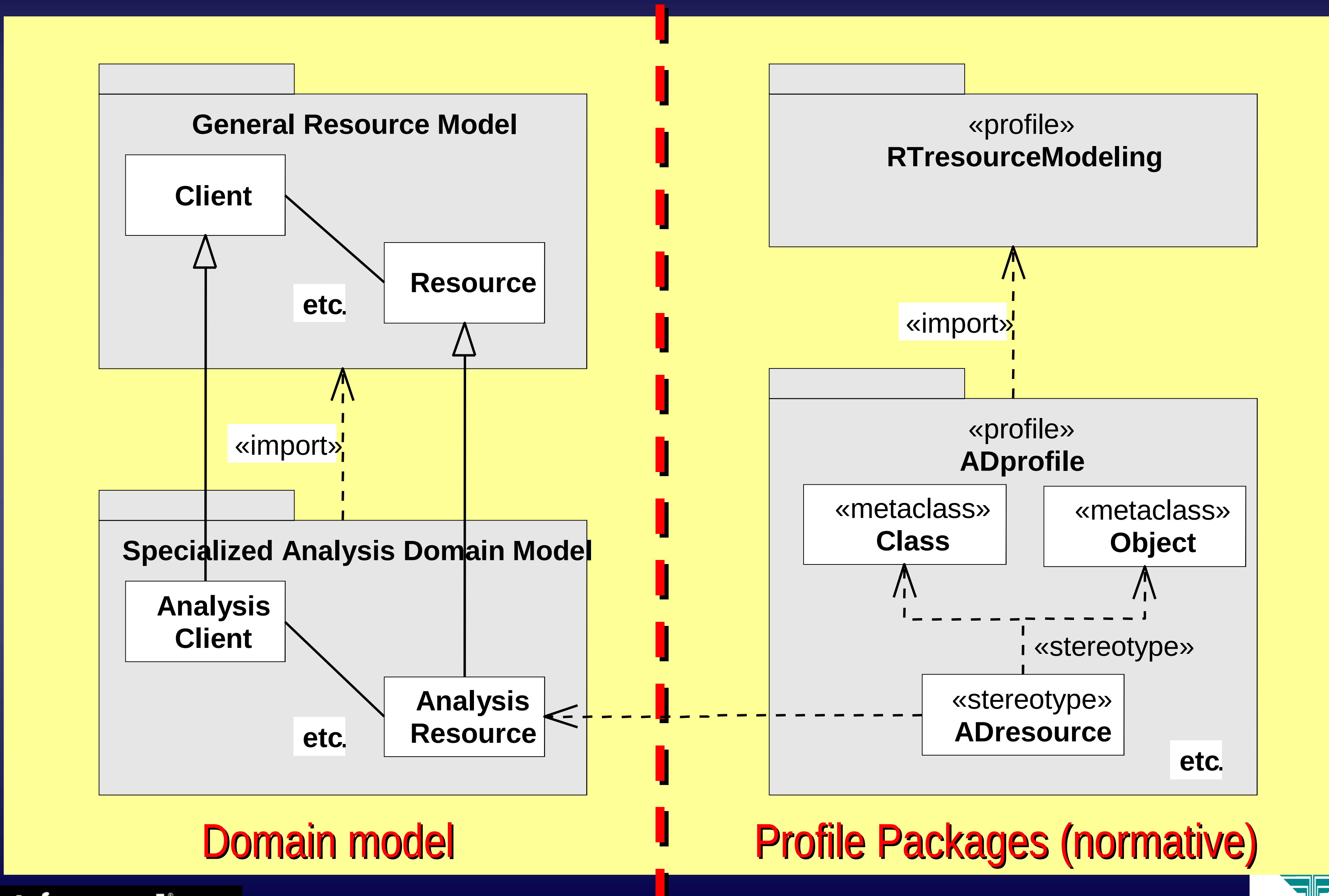


Desired Development Model

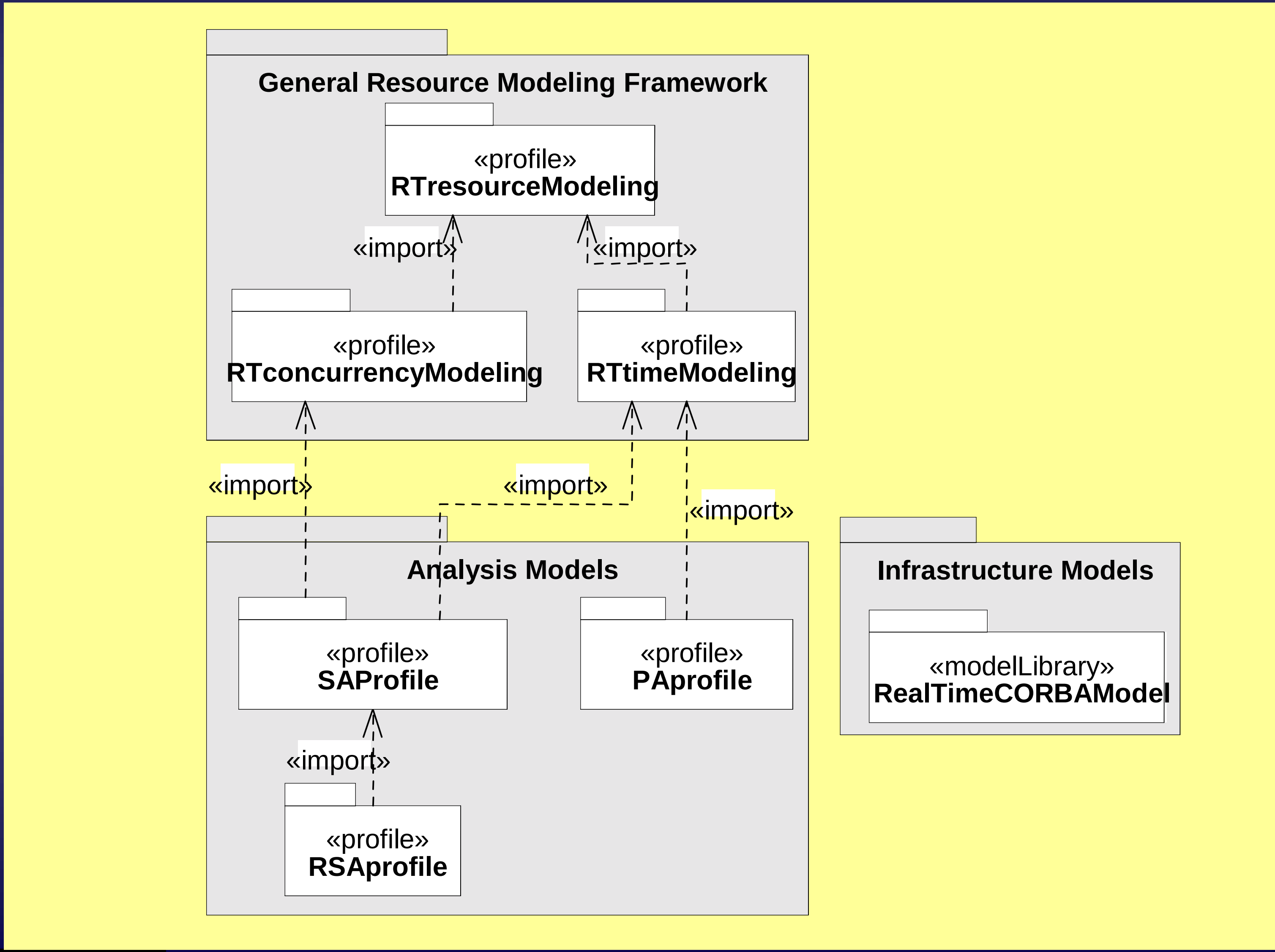
- Seamless integration of technologies and tools based on standards for real-time modeling



Structure: Domain Model and Extensions



UML Real-Time Profile Structure



Quality of Service Concepts

- *Quality of Service (QoS):*

  a specification (usually quantitative) of how a particular service is (to be) performed

  - e.g. throughput, capacity, response time

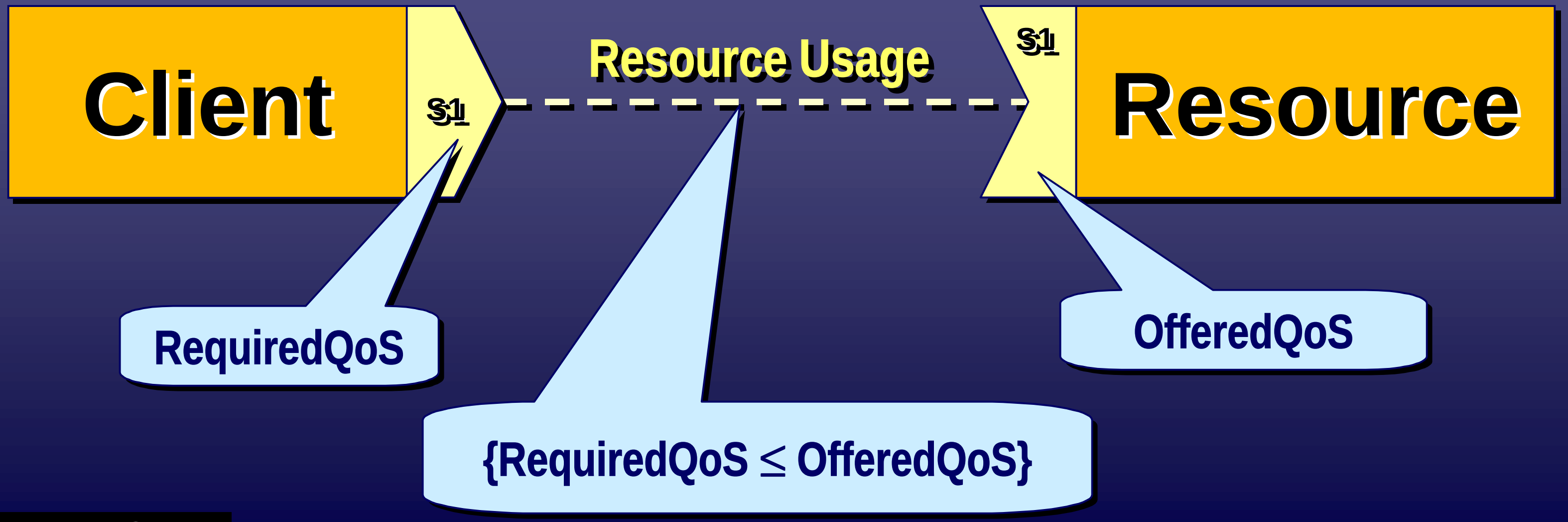
- The specification of a model element can include:
  - *offered QoS:* the QoS that it provides to its clients
  - *required QoS:* the QoS it requires from other components to support its QoS obligations

Resources and Quality of Service

- Resource:

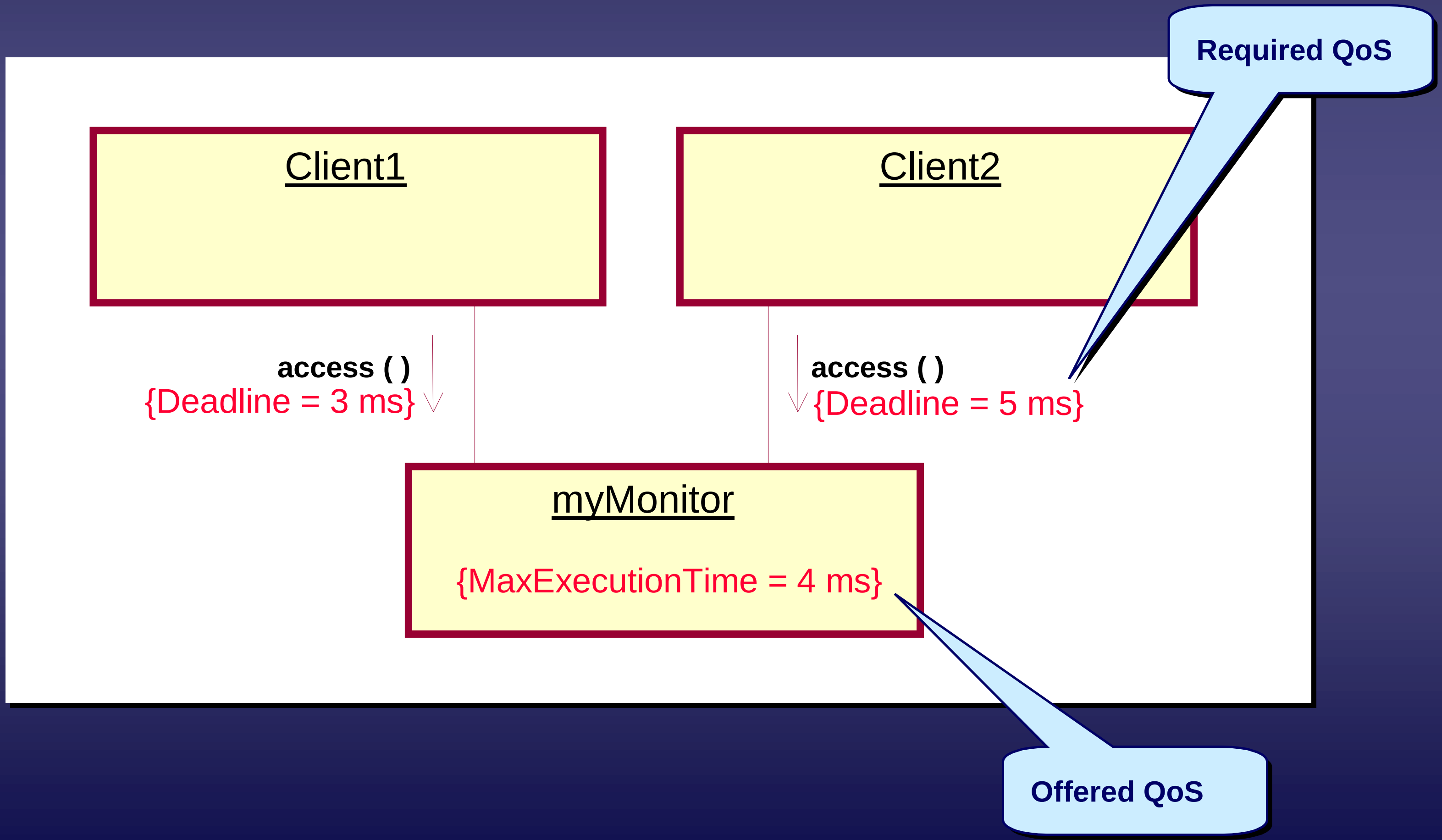
  an element whose service capacity is limited, directly or indirectly, by the finite capacities of the underlying physical computing environment

- These capacities are expressed through QoS attributes of the service or resource

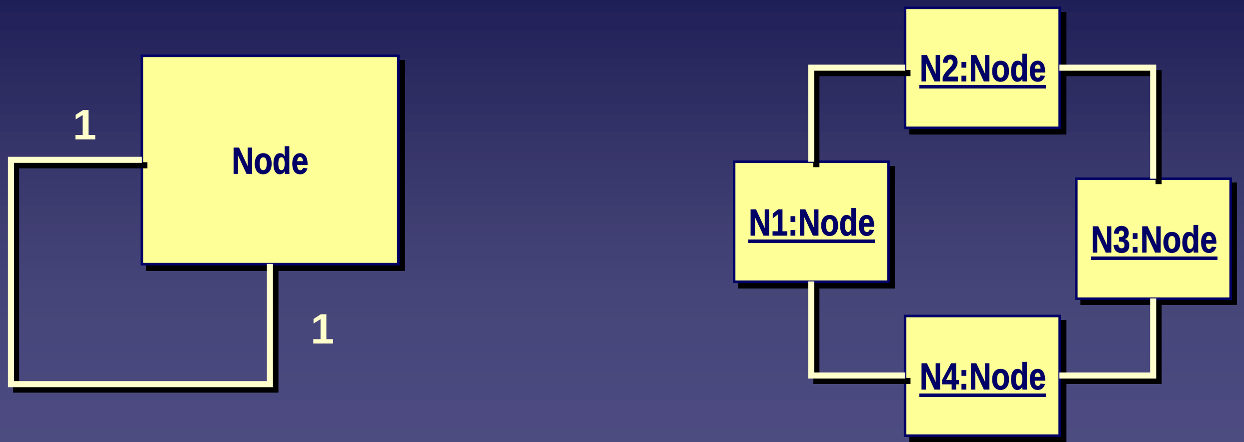


Simple Example

- Concurrent tasks accessing a monitor with known response time characteristics

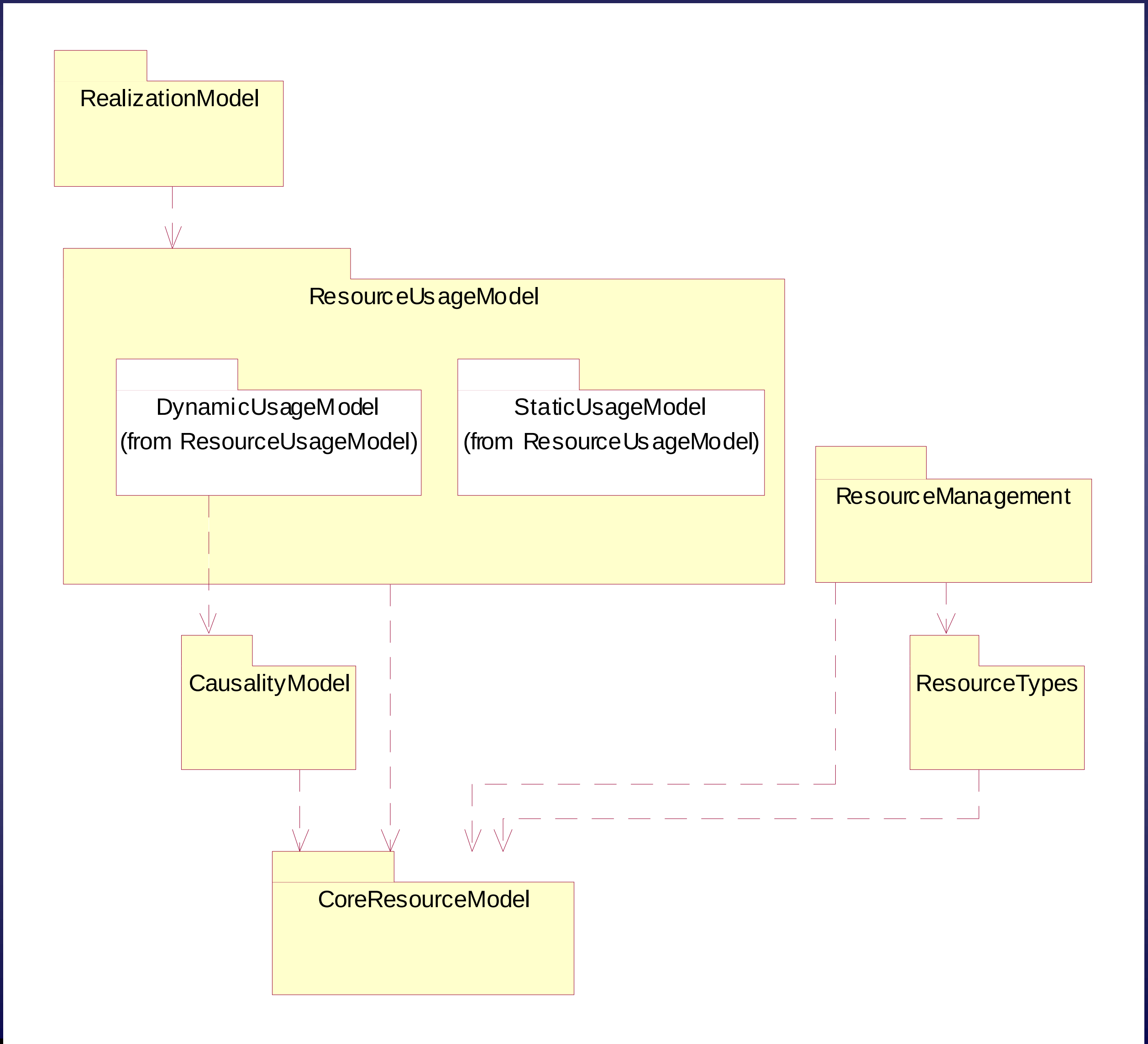


Instance- vs Class-Based Models

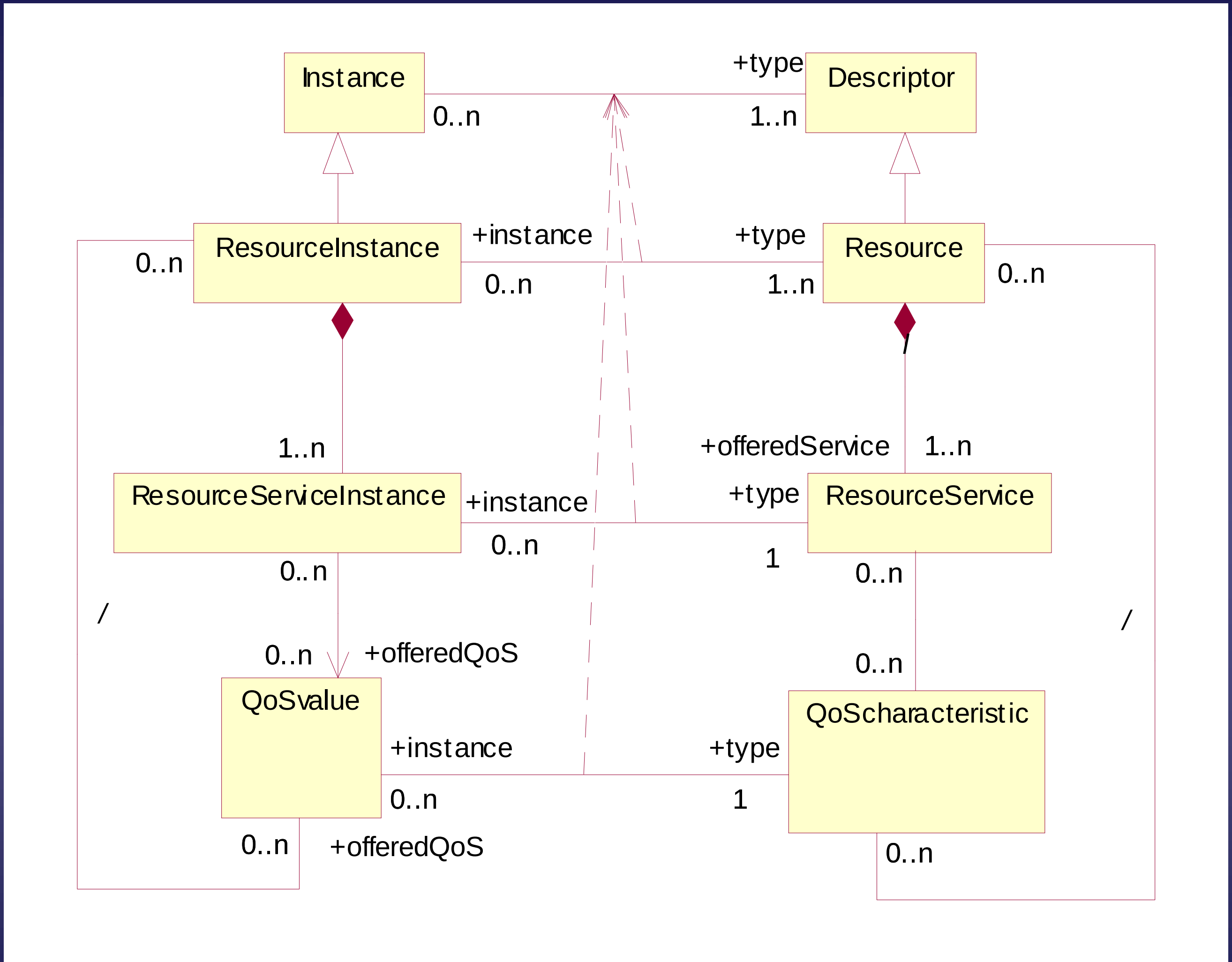


- Practically all analysis methods are concerned with instance-based models
- However, it is often useful to associate QoS characteristics with classes
  - Used to define default values that may be overridden for specific instances
- Need to apply a stereotype to both spec elements and instance elements

The General Resource Model

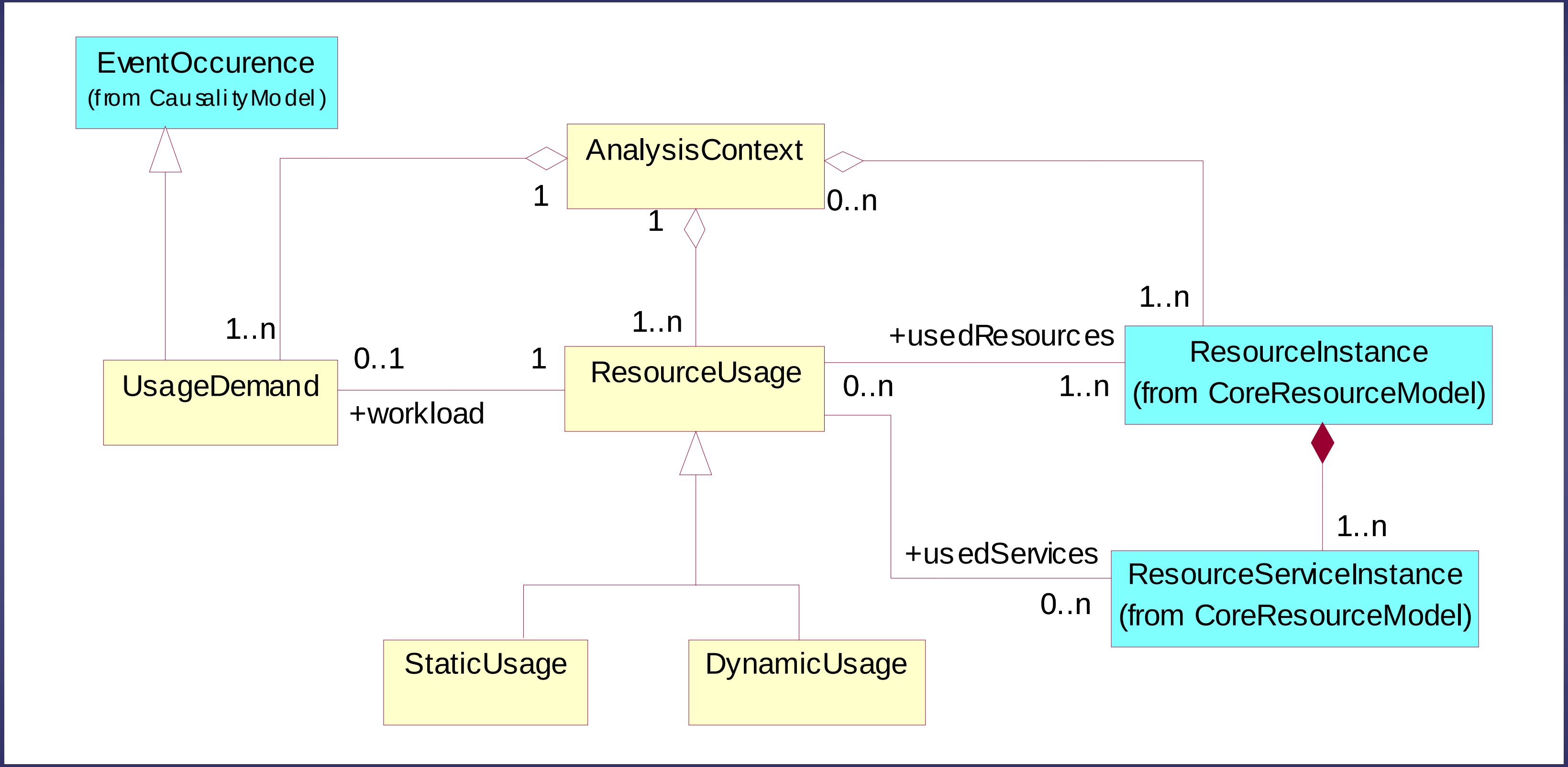


Core Resource Model



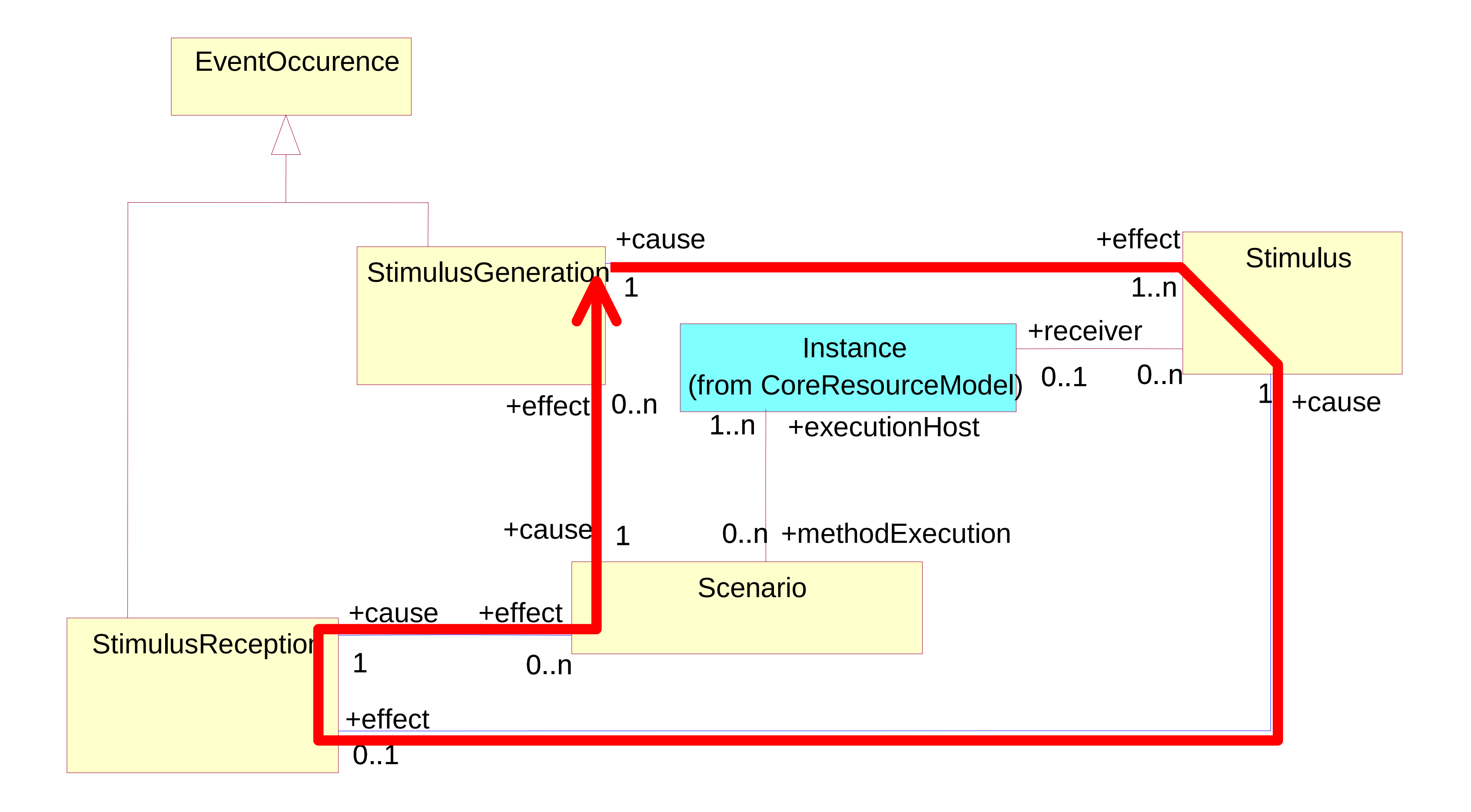
- NB: This is a model of the domain concepts
  - (i.e., it is not a UML metamodel)

Basic Resource Usage Model

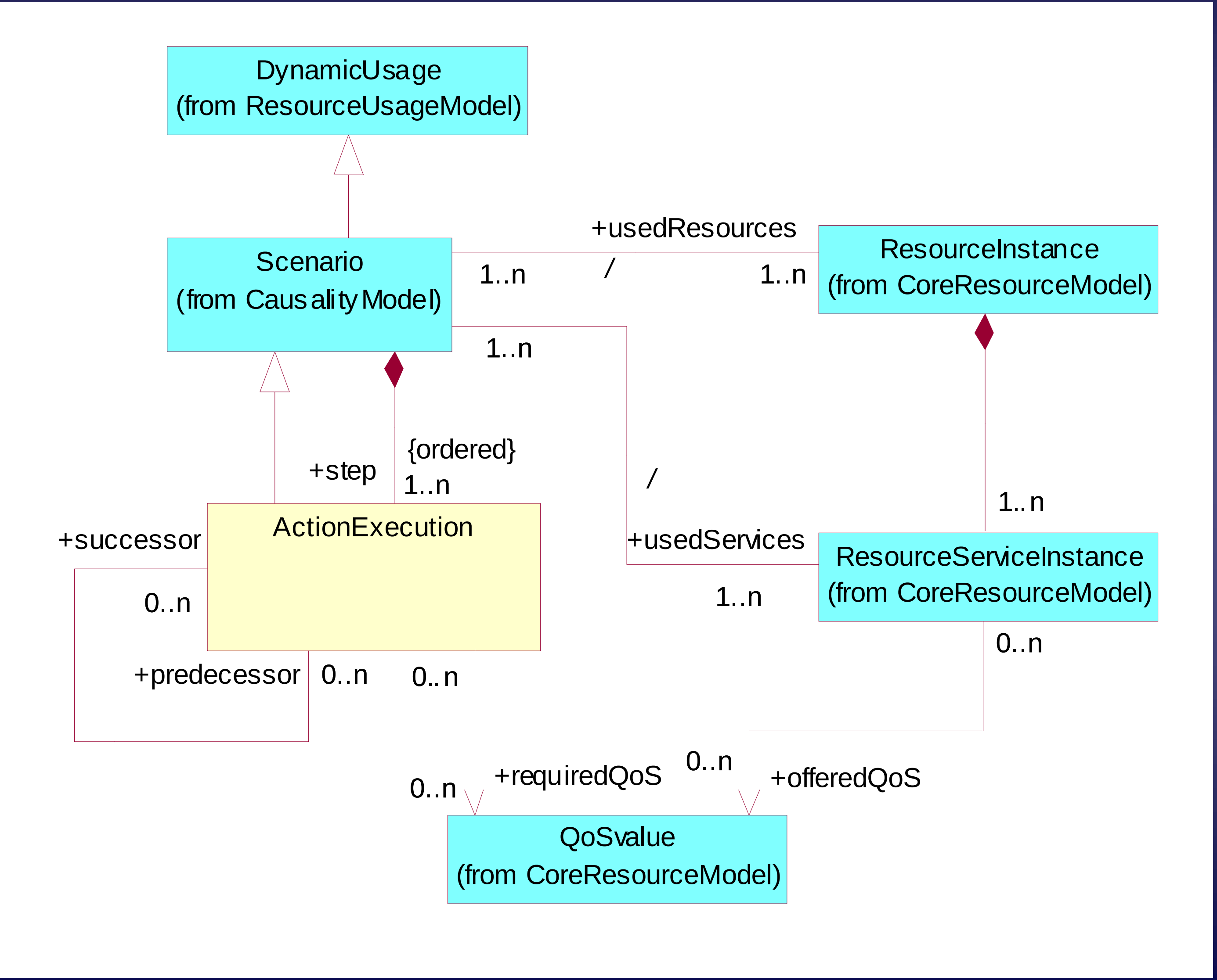


Basic Causality Loop

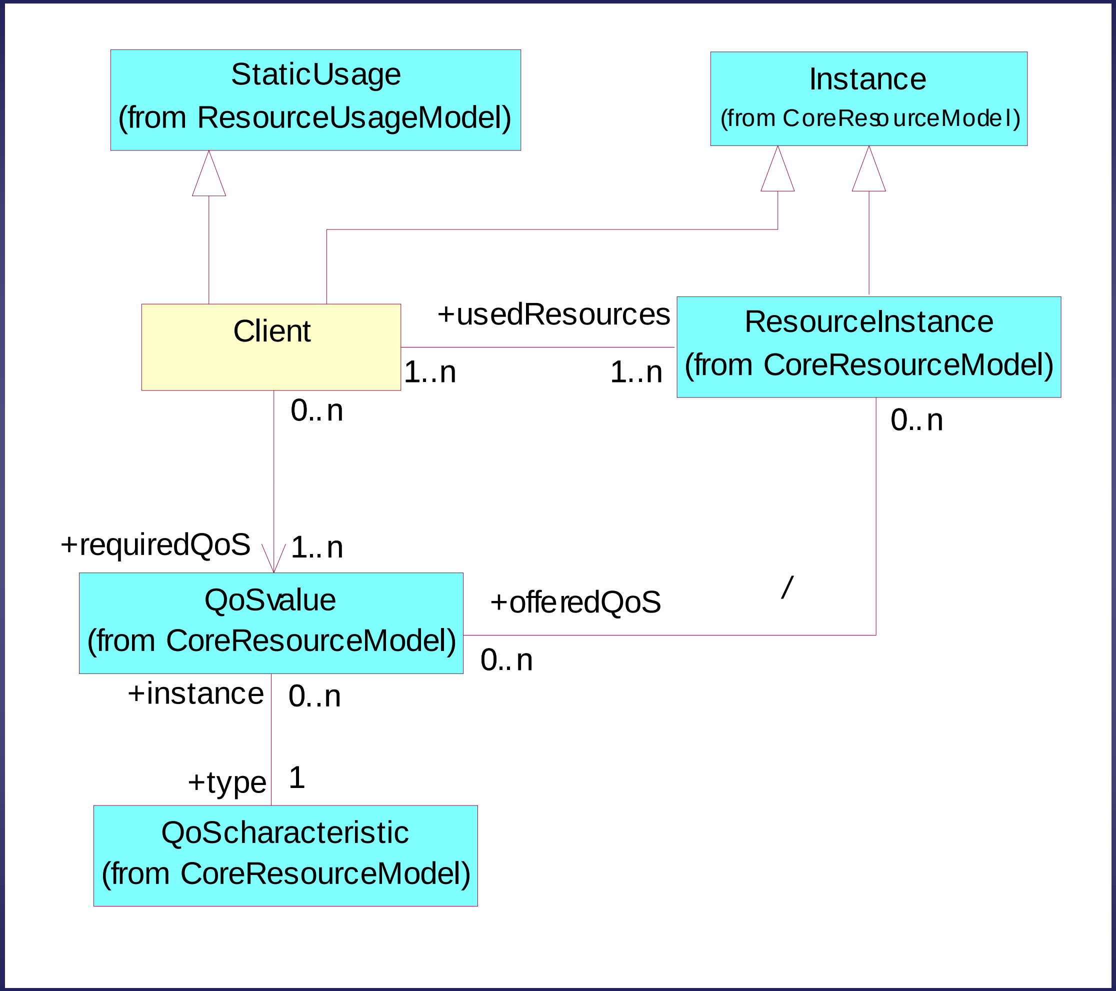
- Used in modeling dynamic scenarios



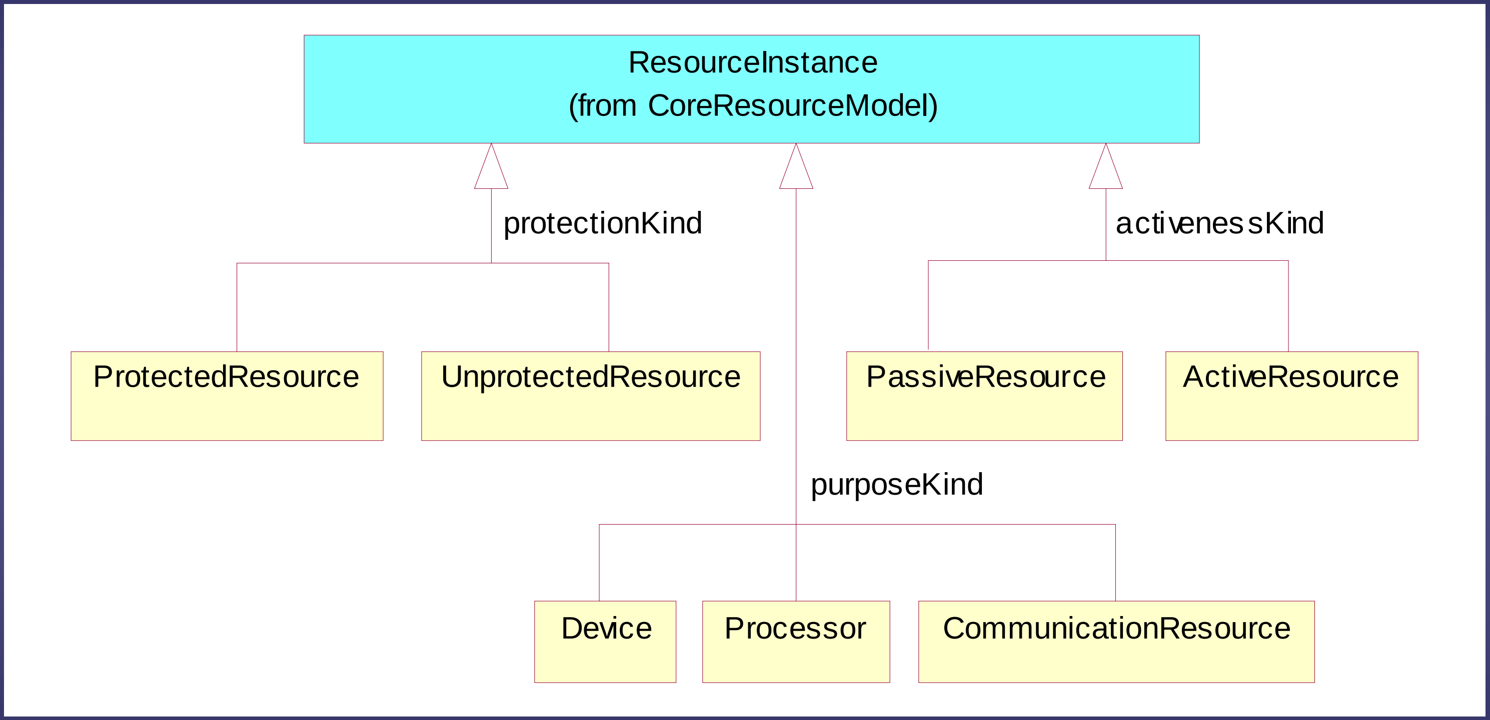
Dynamic Usage Model



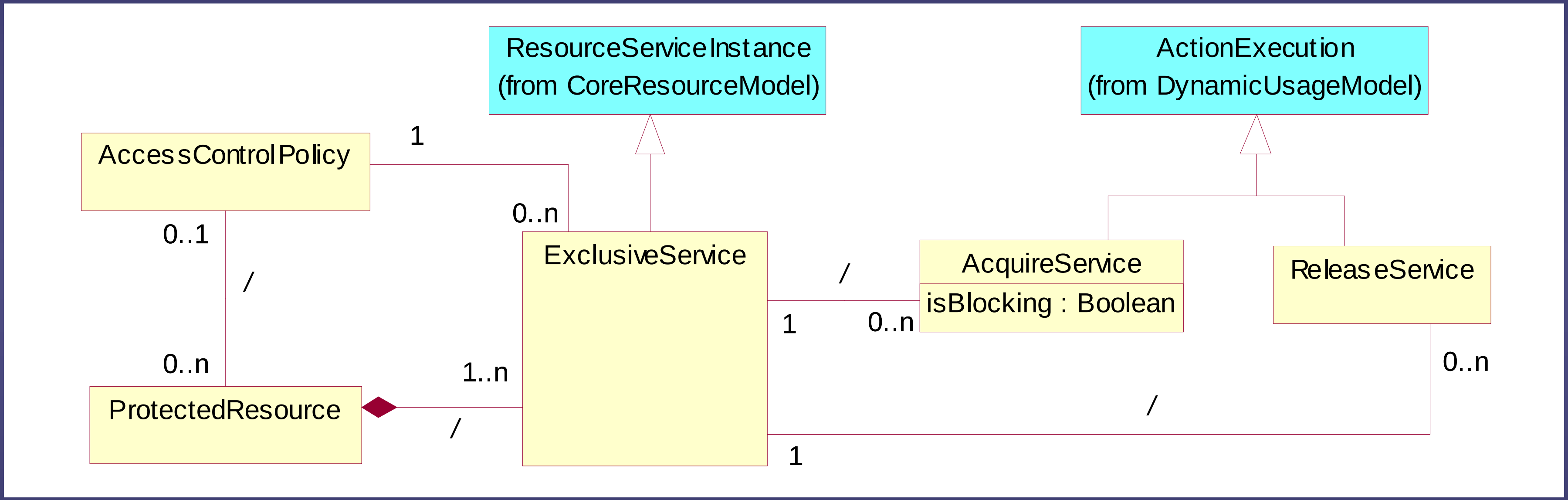
Static Usage Model



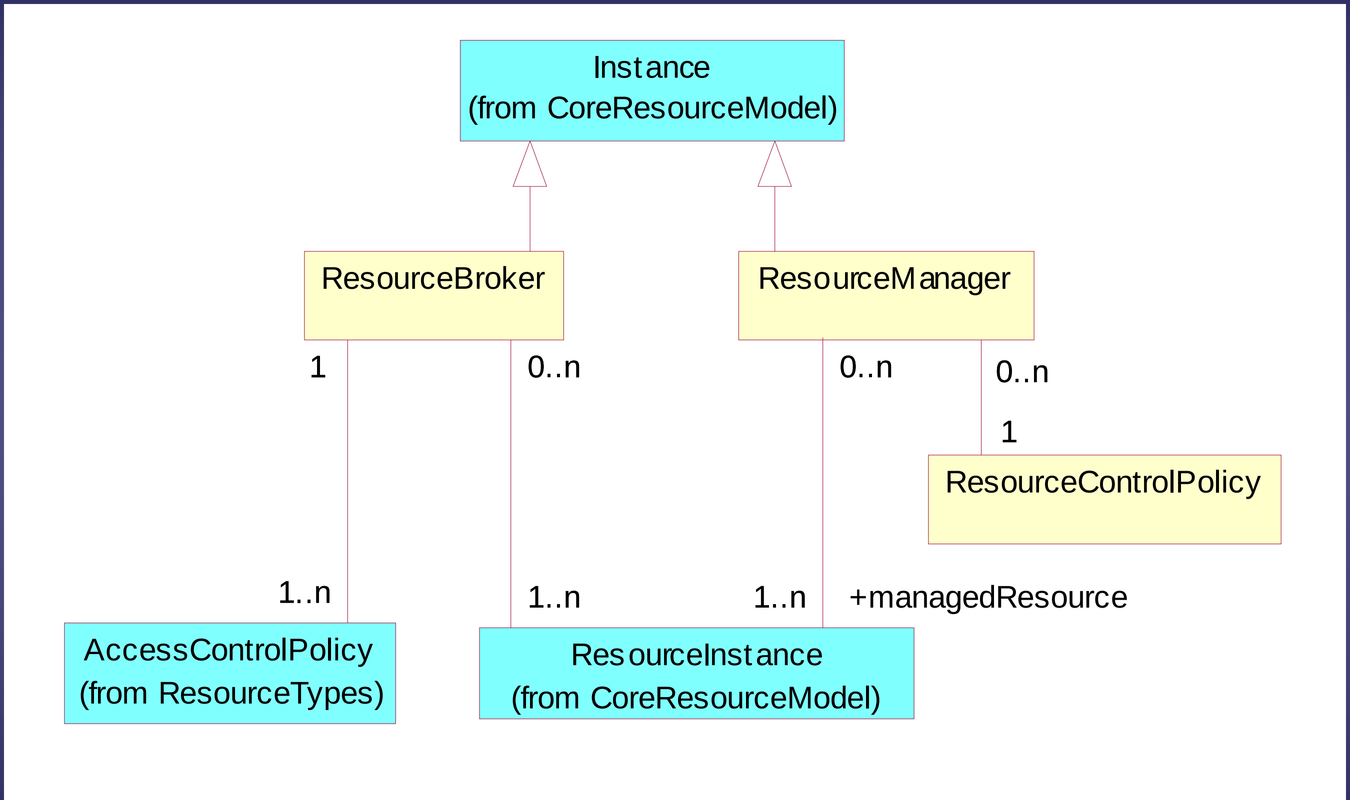
Resource Categorizations



Exclusive Use Resources and Actions

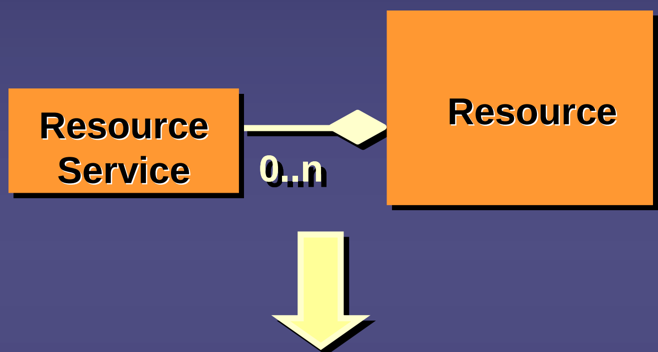


Resource Management Model

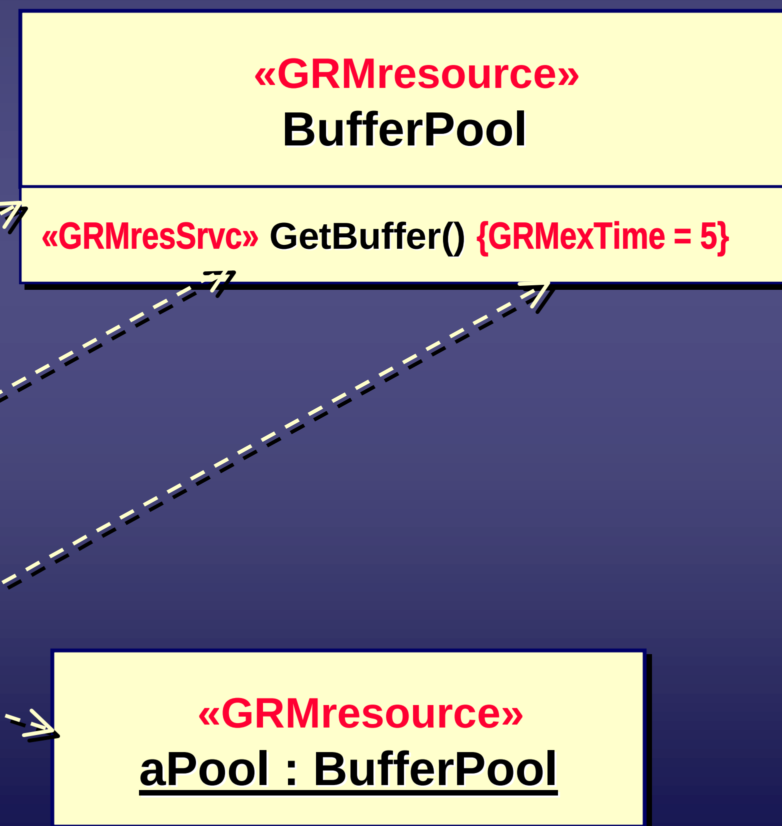


Mapping to UML Extensions

- Elements of the general resource model are represented as stereotypes (with tags) of base UML concepts:

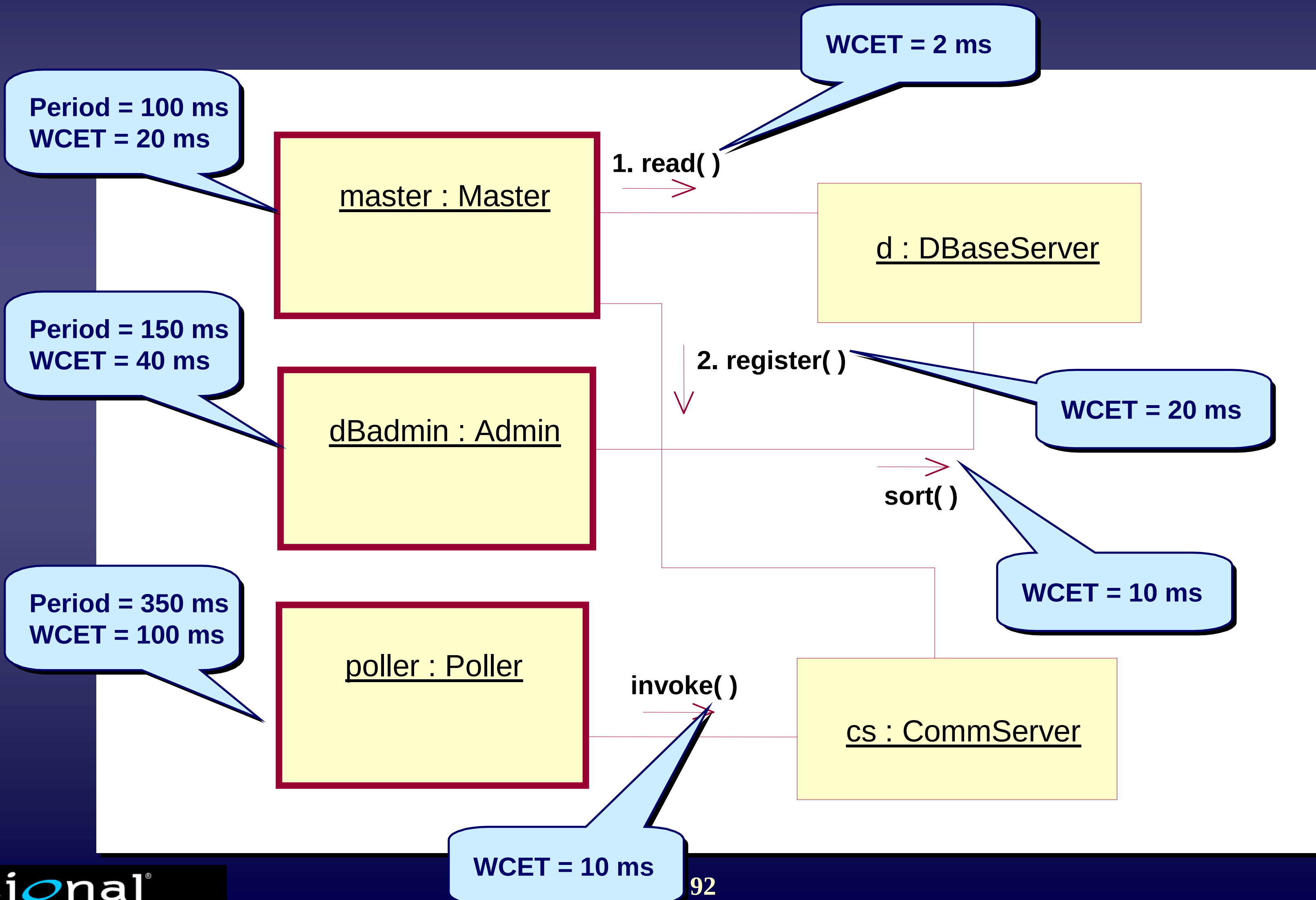


Stereotype	UML base concepts	Tags
GRMresource	Classifier, Instance	N/A
GRMresSrvc	BehavioralFeature	GRMexTime



Example System

- Periodic concurrent tasks sharing resources



Standard Stereotypes

- To allow an analysis tool to extract the necessary QoS information, we define a set of standard stereotypes and related tags*

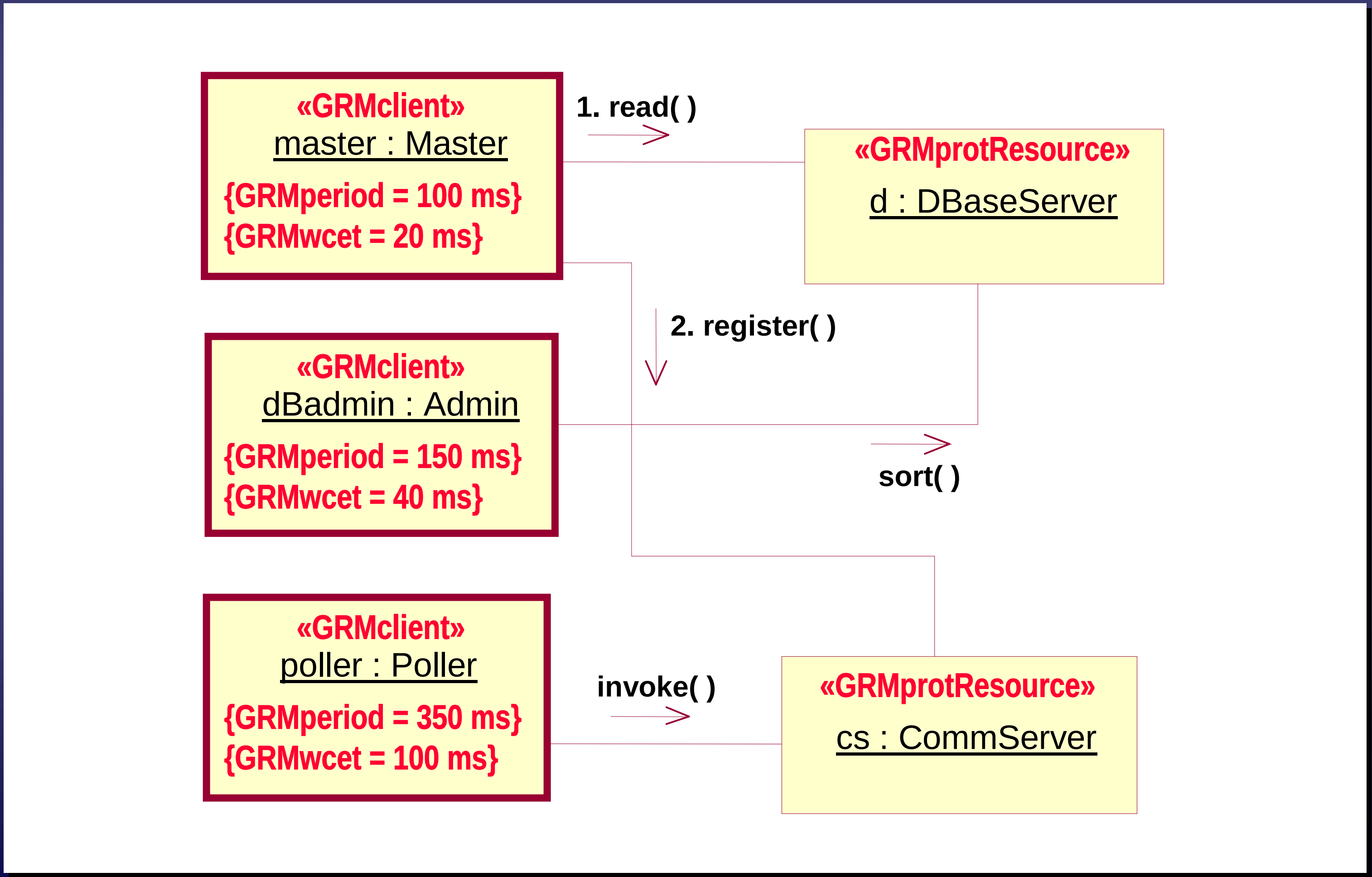
Stereotype	UML base concepts	Tags
GRMclient	Classifier, Instance	GRMperiod, GRMwcet
GRMprotResource	Classifier, Instance	N/A
GRMresService	BehavioralFeature	GRMwcet

Tag	Tag Type
GRMperiod	RTtimeString
GRMwcet	RTtimeString

* The stereotypes and tags have been simplified for this presentation

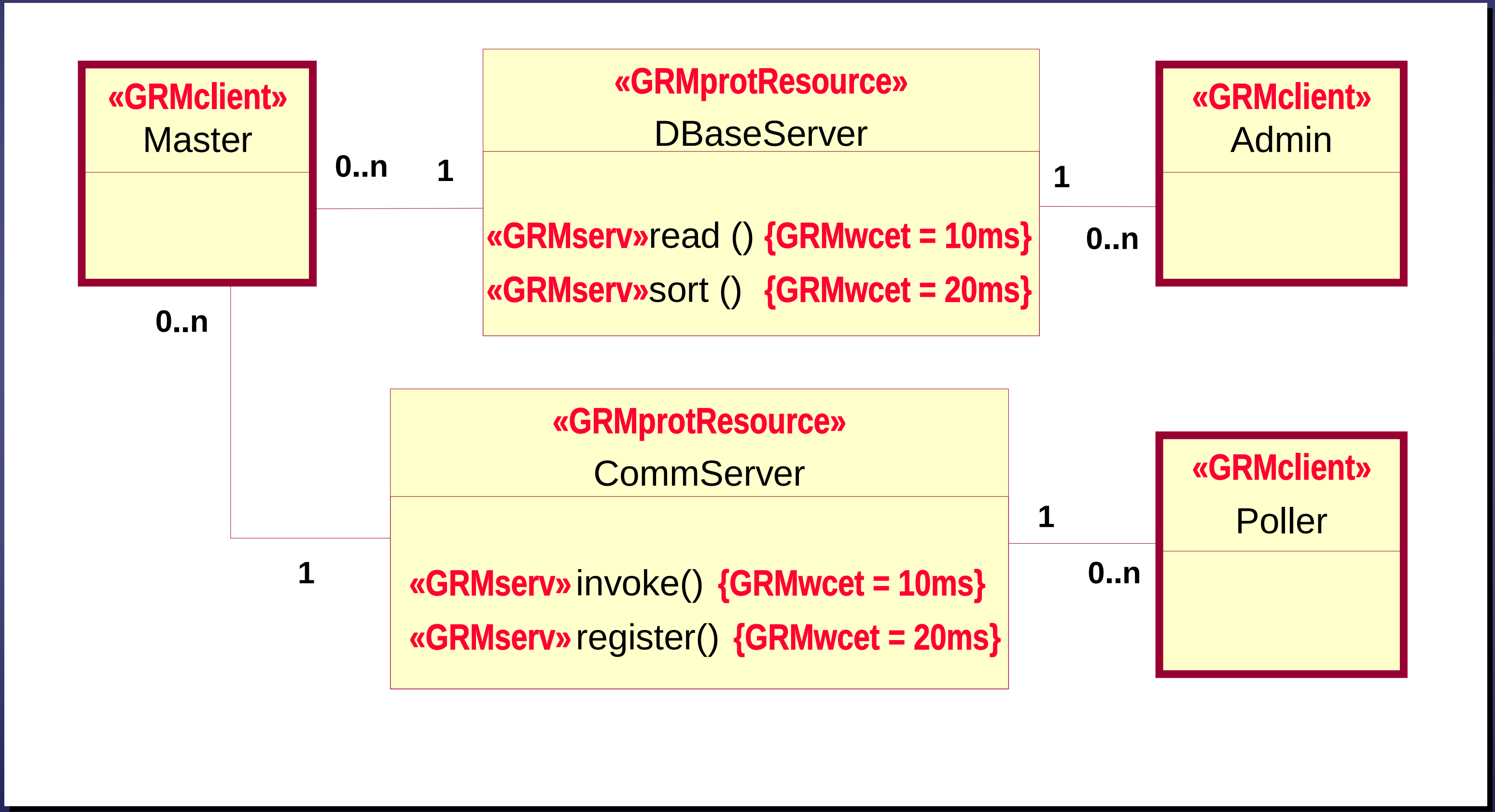
Example: QoS Annotations

- Using the standard stereotypes...

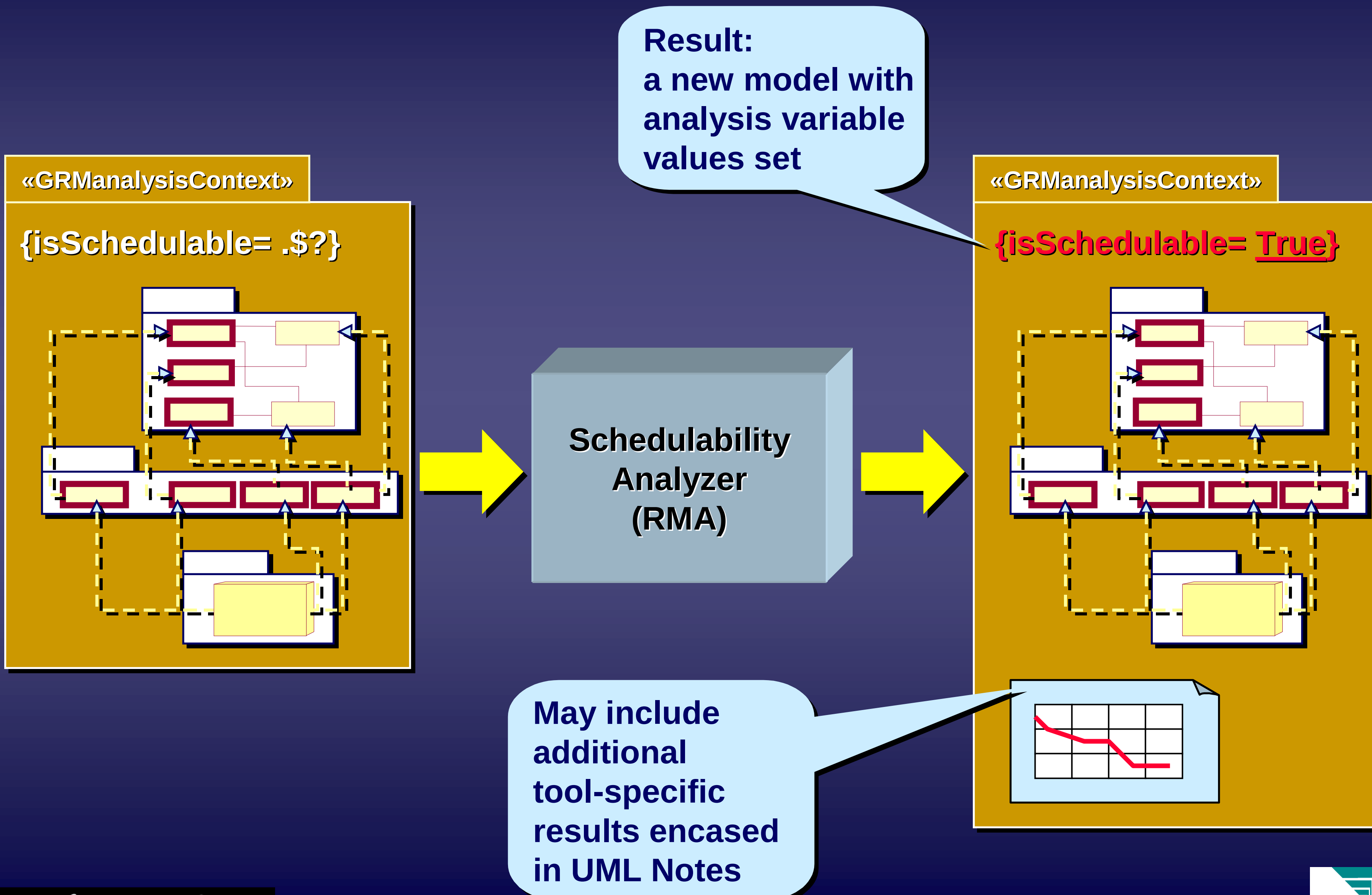


Example: Class Diagram

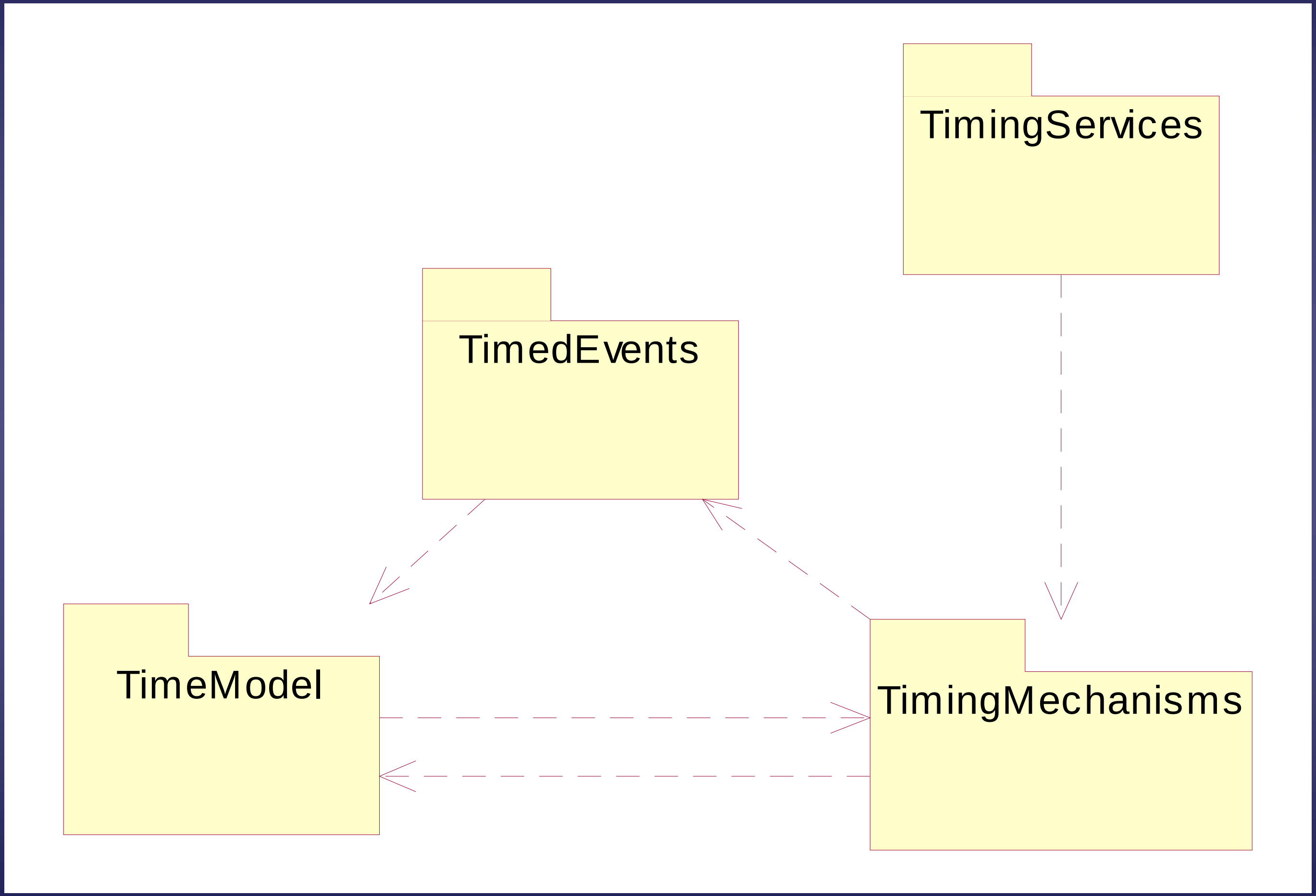
- QoS annotations can be added to classes as well



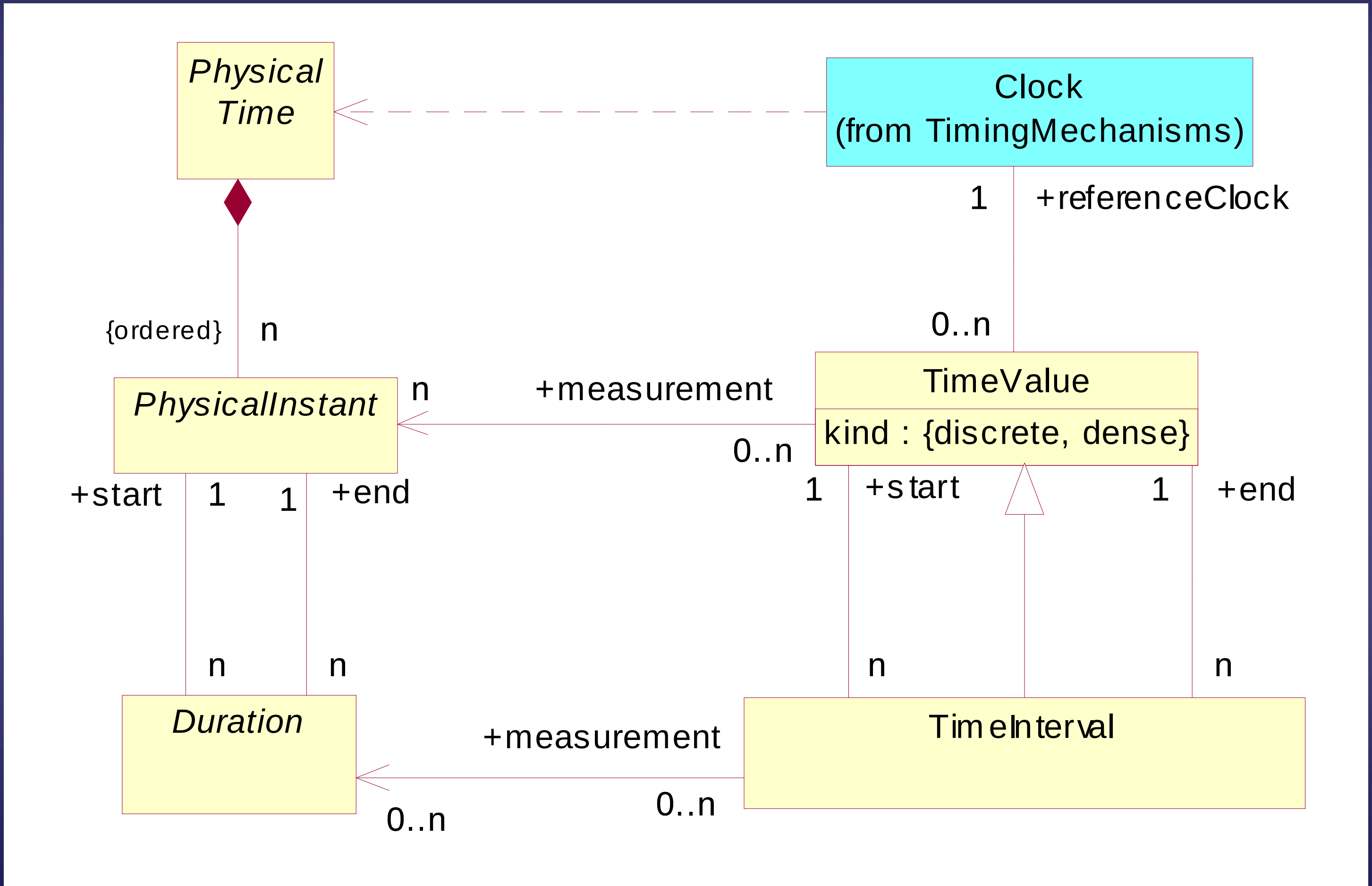
Example: Model Analysis



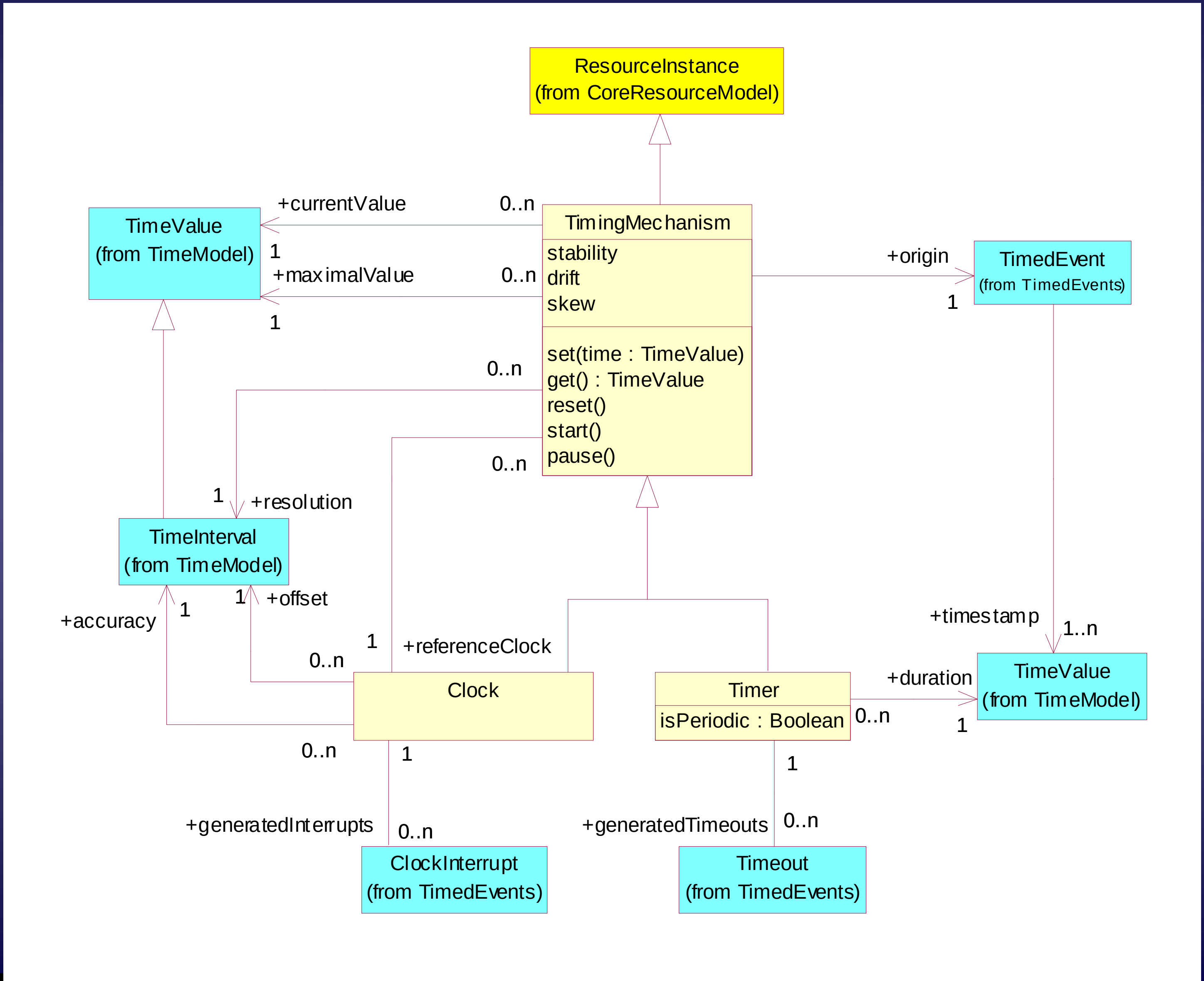
General Time Model



Physical and Measured Time



Timing Mechanisms Model

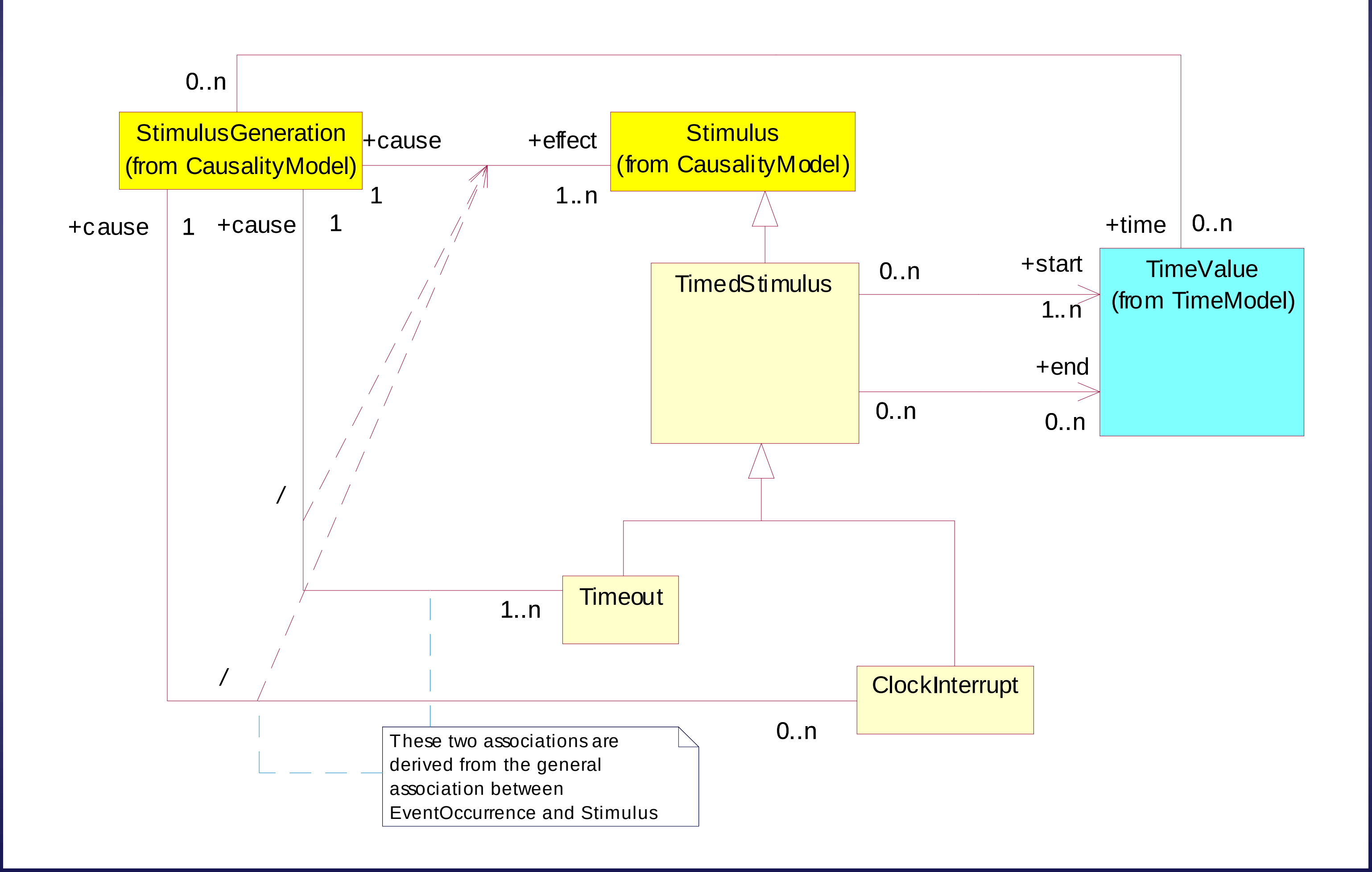


Example Timing Stereotype

Stereotype	Base Class	Tags
«RTaction»	Action	RTstart RTend RTduration
	ActionExecution	
	Message	
	Stimulus	
	Method	
	ActionSequence	
	ActionState	
	SubactivityState	
	Transition	
	State	

Tag	Tag Type	Multiplicity	Domain Name
RTstart	RTtimeValue	[0..1]	TimedAction::start
RTend	RTtimeValue	[0..1]	TimedAction::end
RTduration	RTtimeValue	[0..1]	TimedAction::duration

Timed Stimuli



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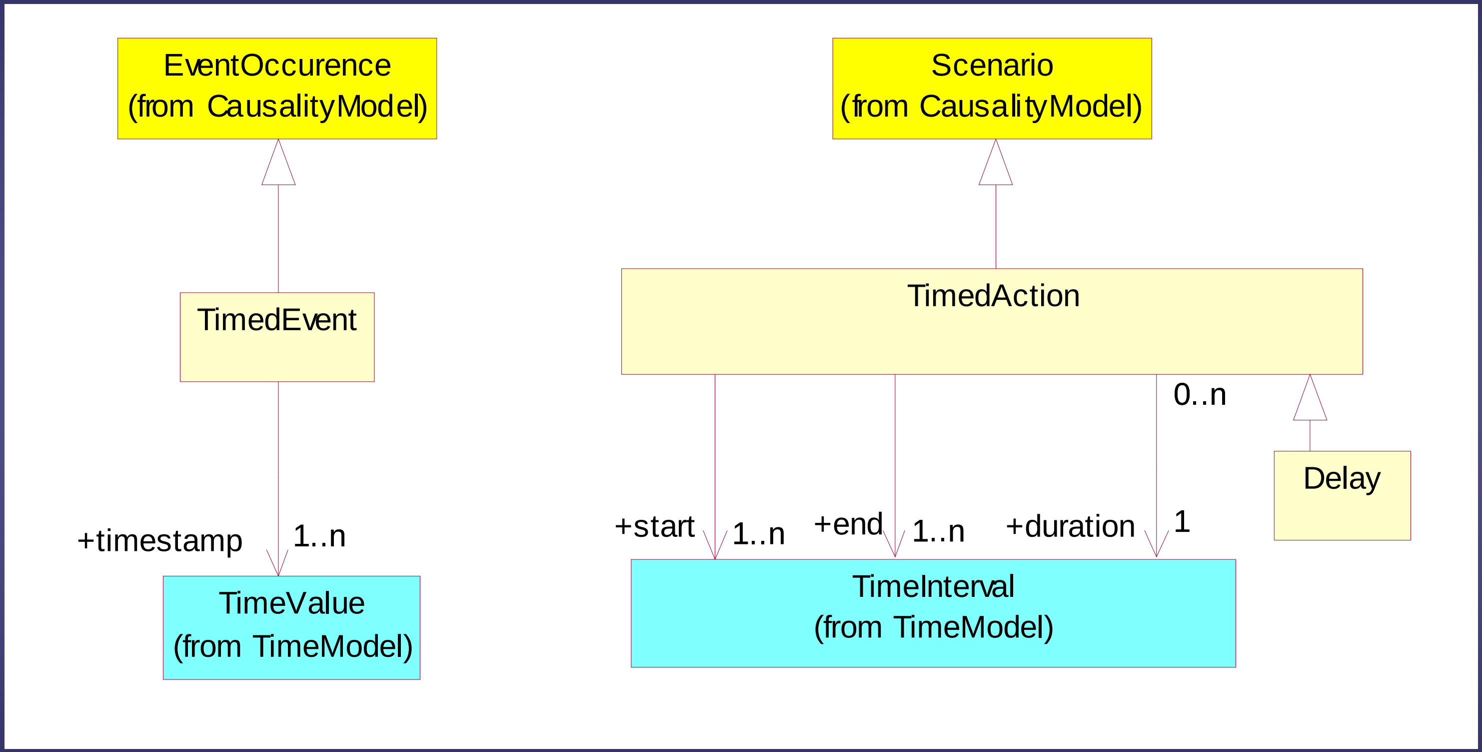
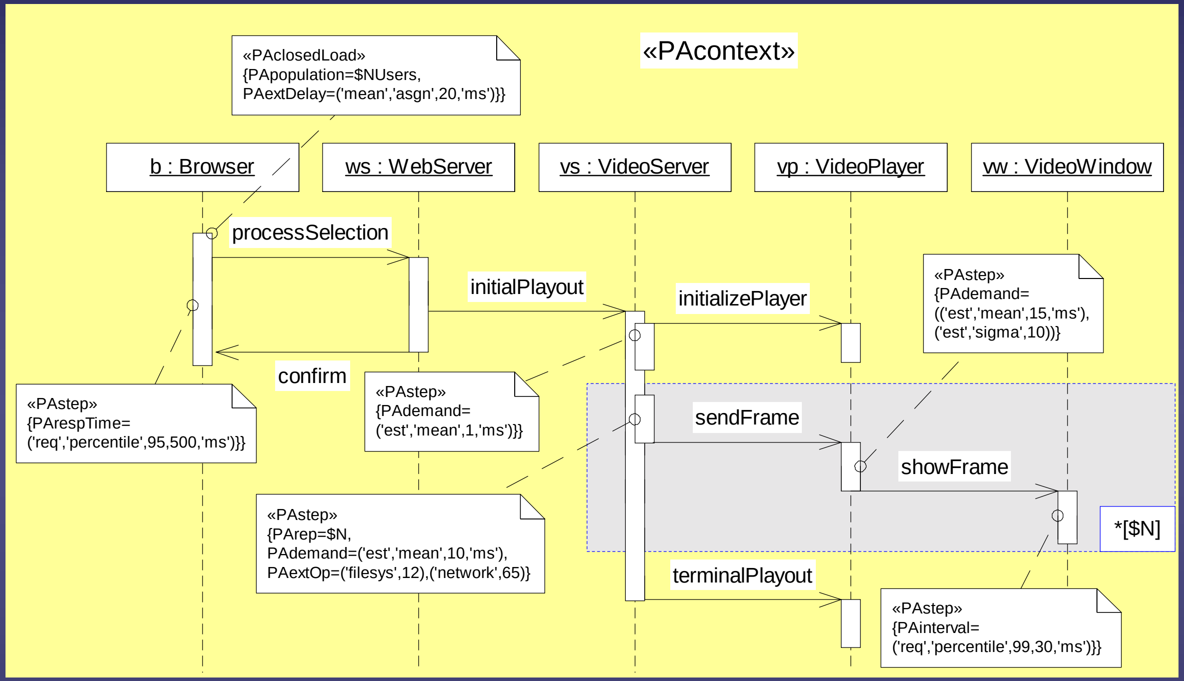
Timed Events and Timed Actions

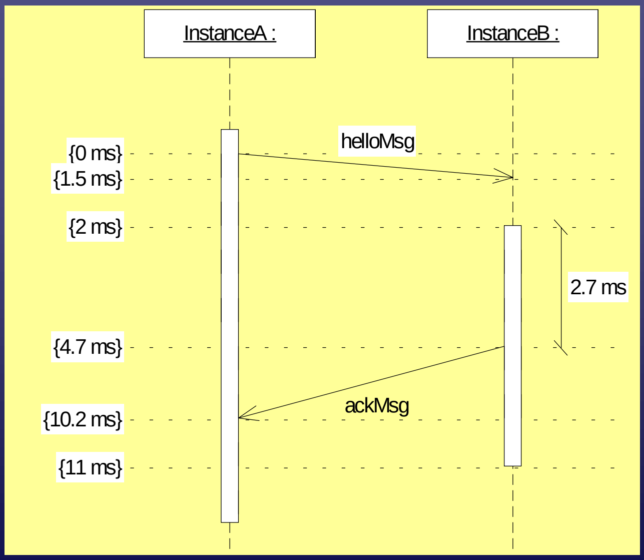


Time Annotations

- In various behavioral diagrams (sequence, activity, state)



More compact forms are also possible:



May be very sophisticated and express complex time values (instants and durations) including probability distributions, percentile values, etc. (NB: tools can help reduce visual clutter)

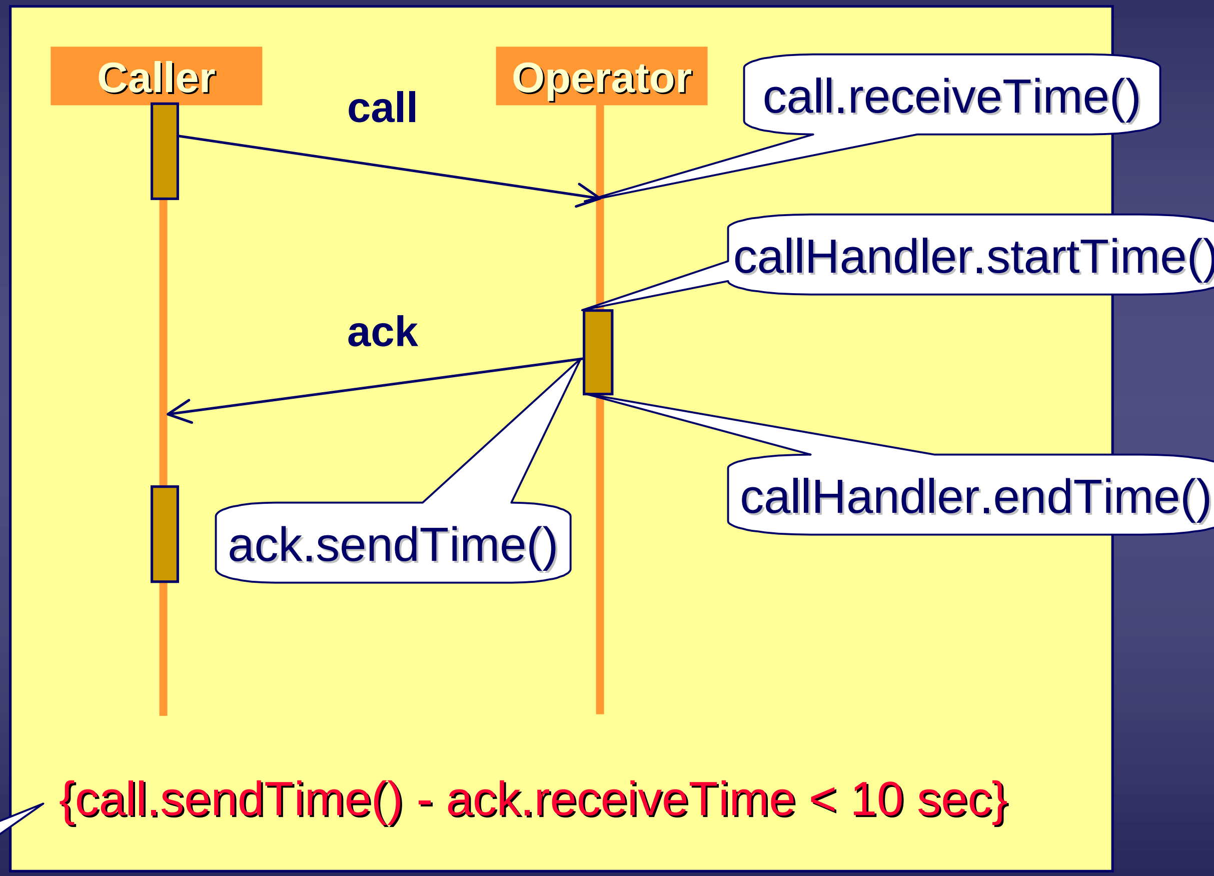
Notation: Timing Marks and Constraints

- A *timing mark* identifies the time of an event occurrence
  - On messages:

    sendTime()
    receiveTime()

  - On action blocks (new):

    startTime()
    endTime()



Timing constraint

Defined Stereotypes (1 of 3)

Stereotype	Applies To	Tags	Description
«RTaction»	Action, ActionExecution, Stimulus, Action, Message, Method…	RTstart [0..1] RTend [0..1] RTduration [0..1]	An action that takes time
«RTclkInterrupt» (subclass of «RTstimulus»)	Stimulus, Message	RTtimestamp [0..1]	A clock interrupt
«RTclock» (subclass of «RTtimingMechanism»)	Instance, DataType, Classifier, ClassifierRole…	RTclockId [0..1]	A clock mechanism
«RTdelay»	Action, ActionExecution, Stimulus, Action, Message, Method…	RTduration [0..1]	A pure delay activity
«RTevent»	Action, ActionExecution, Stimulus, Action, Message, Method…	RTat [0..1]	An event that occurs at a known time instant
«RTinterval»	Instance, Object, Classifier, DataType, DataValue	RTintStart [0..1] RTintEnd [0..1] RTintDuration [0..1]	A time interval

Defined Stereotypes (2 of 3)

Stereotype	Applies To	Tags	Description
«RTnewClock	Operation	RTstart [0..1] RTend [0..1] RTduration [0..1]	An operation that creates a new clock mechanism
«RTnewTimer»	Operation	RTtimerPar [0..1]	An operation that creates a new timer
«RTpause»	Operation		A pause operation on a timing mechanism
«RTreset»	Operation		An operation that resets a timing mechanism
«RTset»	Operation	RTtimePar [0..1]	An operation that sets the current value of a timing mechanism
«RTstart»	Operation		An operation that starts a timing mechanism
«RTstimulus»	Stimulus, ActionExecution, Action, ActionSequence, Method	RTstart [0..1] RTend [0..1]	A timed stimulus

Defined Stereotypes (3 of 3)

Stereotype	Applies To	Tags	Description
«RTtime»	DataValue, Instance, Object, DataType, Classifier	RTkind [0..1] RTrefClk [0..1]	A time value or a time object
«RTtimeout» (subclass of «RTstimulus»)	Stimulus, ActionExecution, Action, ActionSequence, Method	RTtimestamp [0..1]	A timeout signal or a timeout action
«RTtimer» (subclass of «RTtimingMechanism»)	DataValue, Instance, Object, ClassifierRole, Classifier…	RTduration [0..1] RTperiodic [0..1]	A timer mechanism
«RTtimeService»	Instance, Object, ClassifierRole, Classifier		A time service
«RTtimingMechanism»	DataValue, Instance, Object,ClassifierRole, Classifier, DataType	RTstability [0..1] RTdrift [0..1] RTskew [0..1] RTmaxValue [0..1] RTorigin [0..1] RTresolution [0..1] RTaccuracy [0..1] RTcurrentVal [0..1] RToffset [0..1] RTrefClk [0..1]	A timing mechanism

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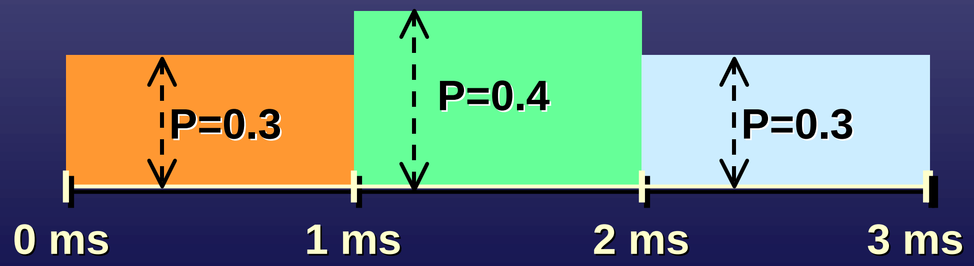
Specifying Time Values

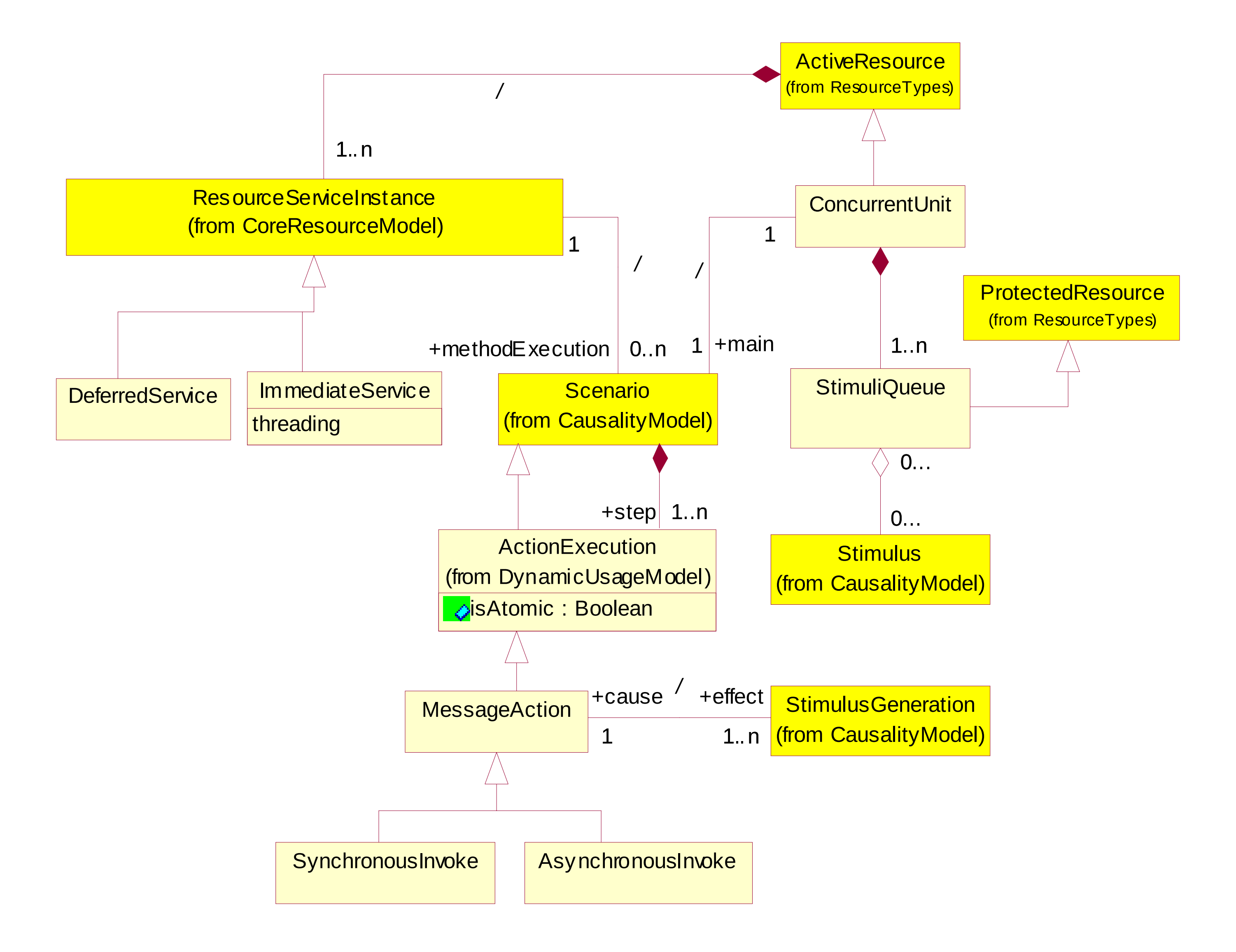
- Time values can be represented by a special stereotype of Value («RTtimeValue») in different formats; e.g.
  - 12:04 (time of day)
  - 5.3, 'ms' (time interval)
  - 2000/10/27 (date)
  - Wed (day of week)
  - $param, 'ms' (parameterized value)
  - 'poisson', 5.4, 'sec' (time value with a Poisson distribution)
  - 'histogram' 0, 0.3 1, 0.4 2, 0.3, 3, 'ms'



Specifying Arrival Patterns

- Method for specifying standard arrival pattern values
  - Bounded: *'bounded', <min-interval>, <max-interval>*
  - Bursty: *'bursty', <burst-interval> <max.no.events>*
  - Irregular: *'irregular', <interarrival-time>, [<interarrival-time>]**
  - Periodic: *'periodic', <period> [, <max-deviation>]*
  - Unbounded: *'unbounded', <probability-distribution>*
- Probability distributions supported:
  - Bernoulli, Binomial, Exponential, Gamma, Geometric, Histogram, Normal, Poisson, Uniform

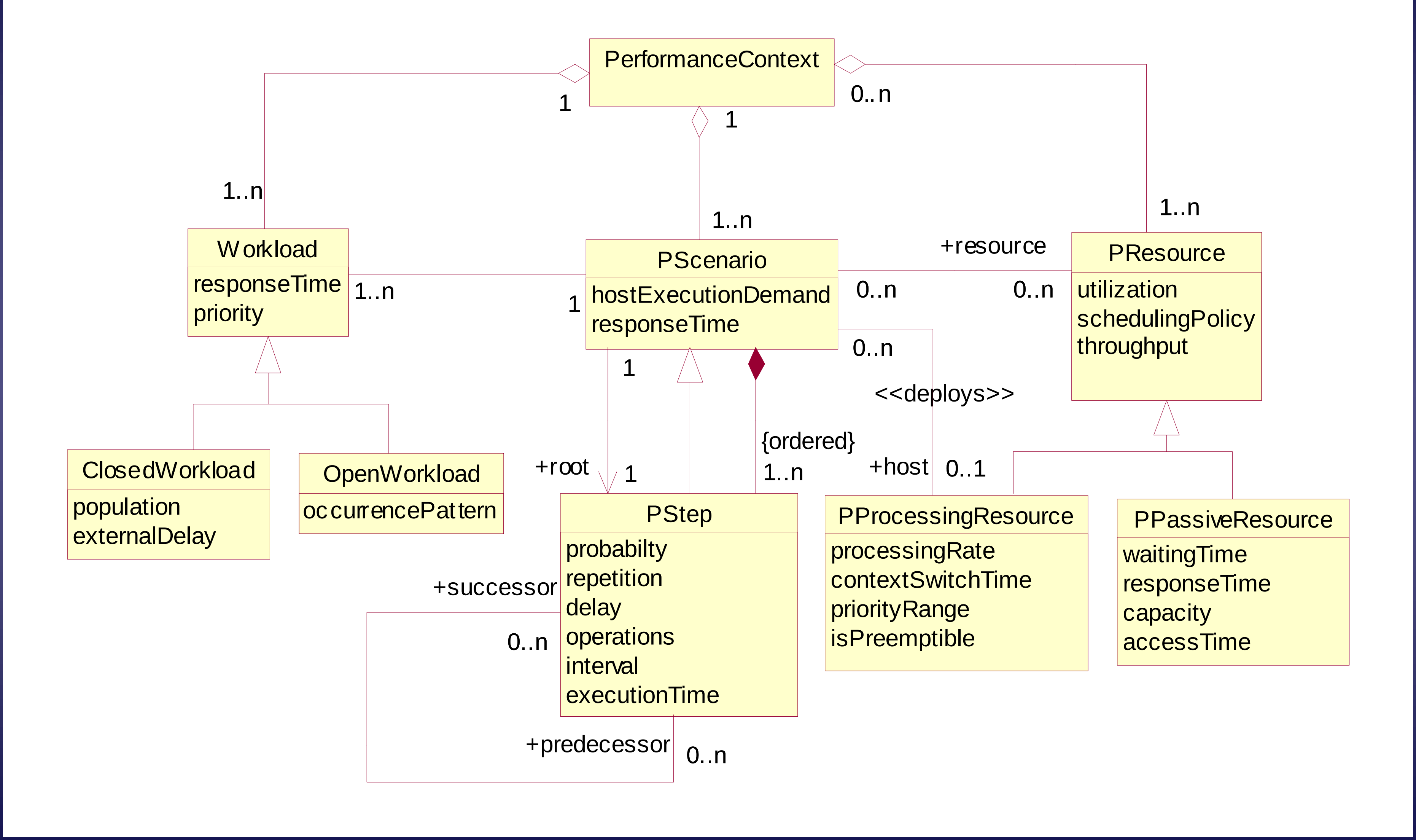
General Concurrency Modeling



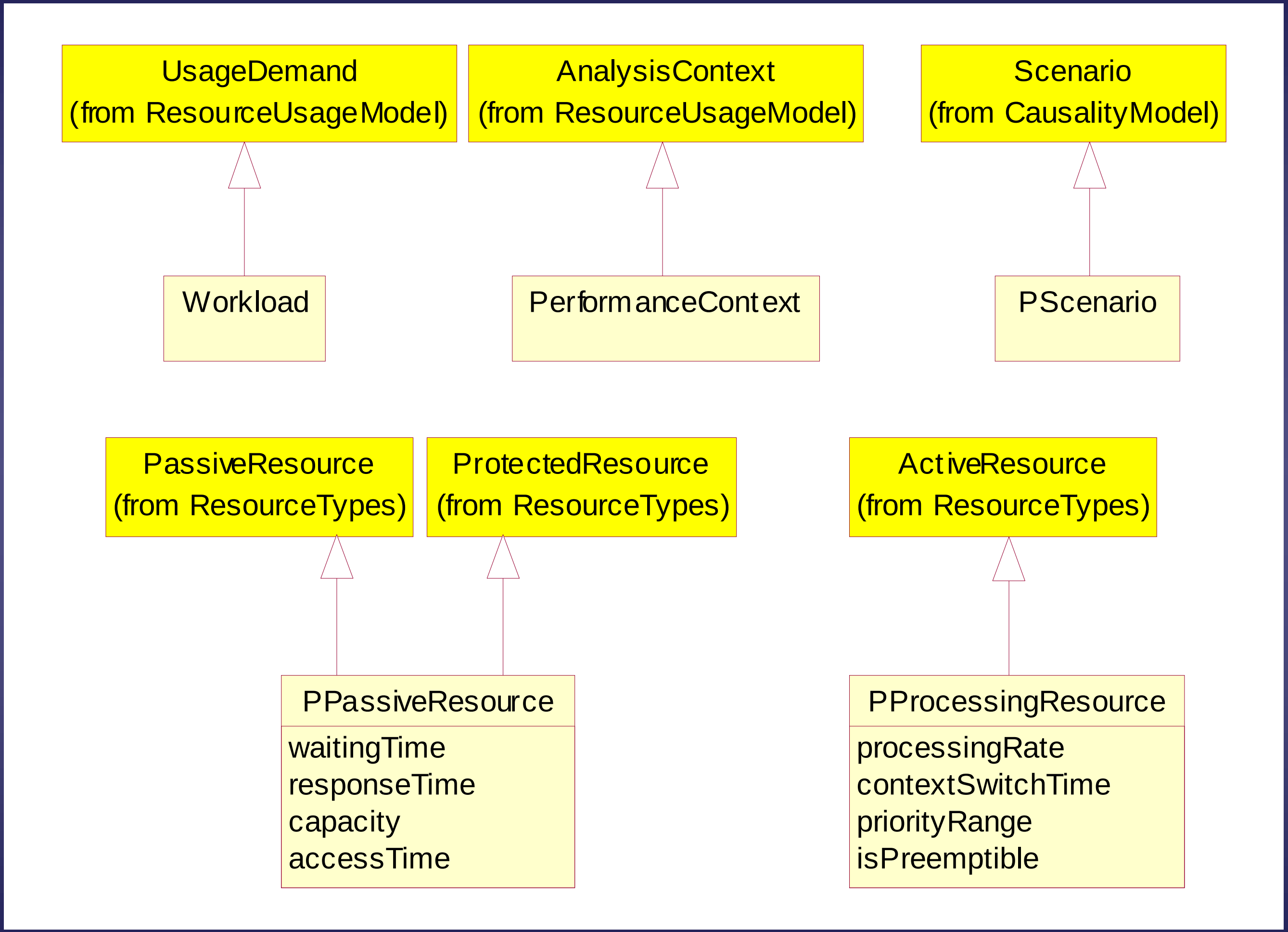
Defined Stereotypes

Stereotype	Applies To	Tags	Description
«CRAction»	Action, ActionExecution, Stimulus, Action, Message, Method…	CRAtomic [0..1]	An action execution
«CRAsynch»	Action, ActionExecution		An asynchronous invocation
«CRConcurrent»	Node, Component, Artifact, Class, Instance	CRMain [0..1]	A concurrent unit concept
«CRContains»	Usage		A generalized usage dependency
«CRDeferred»	Operation, Reception, Message, Stimulus		A deferred receive
«CRImmediate»	Operation, Reception, Message, Stimulus	{remote, local} [0..1]	An instance of an immediate service
«CRmsgQ»	Instance, Object, Class, ClassifierRole		A stimuli queue
«CRSynch»	Action, ActionExecution		A synchronous invoke

Performance Analysis Concepts



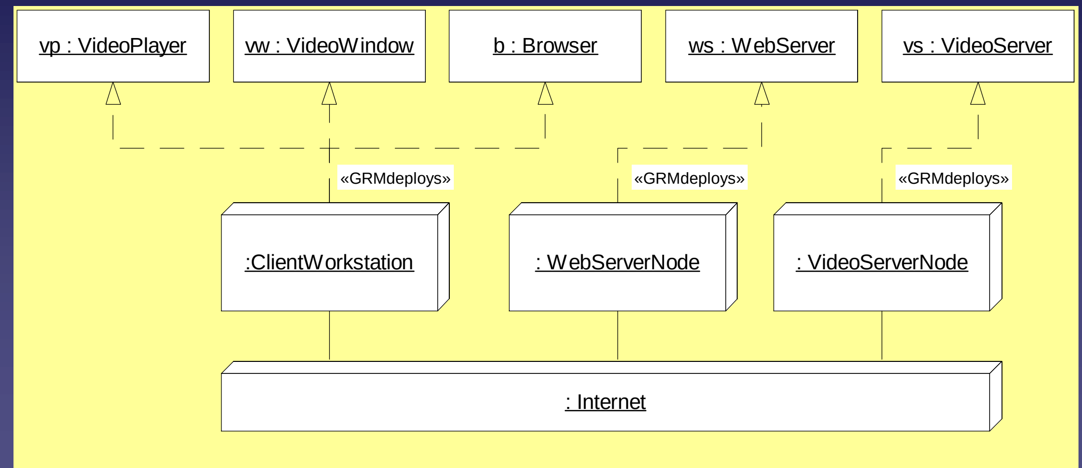
Relationship to General Resource Model



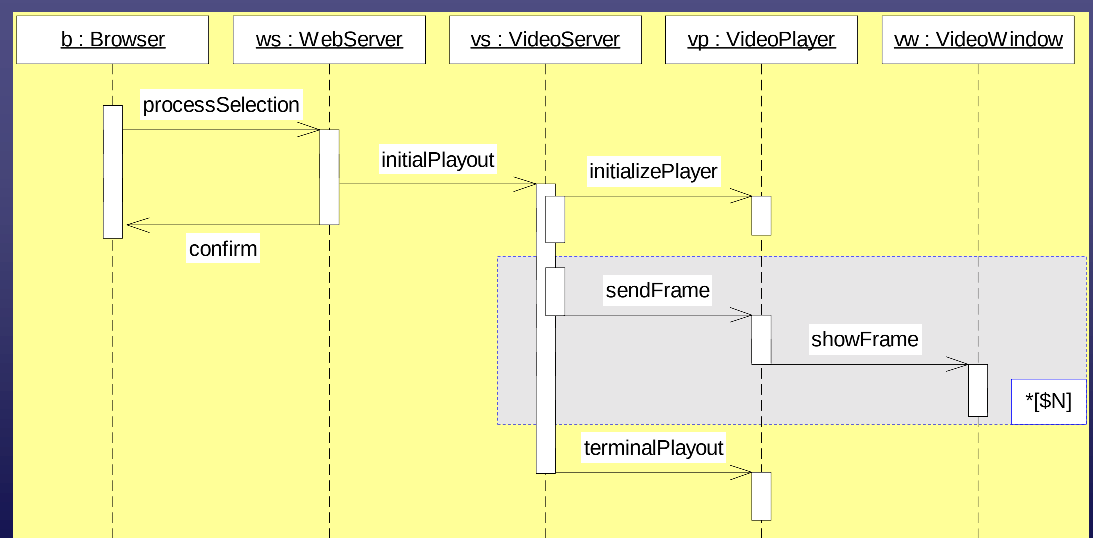
Example: Web Video Application

Logical Instance Model

Engineering Instance Model



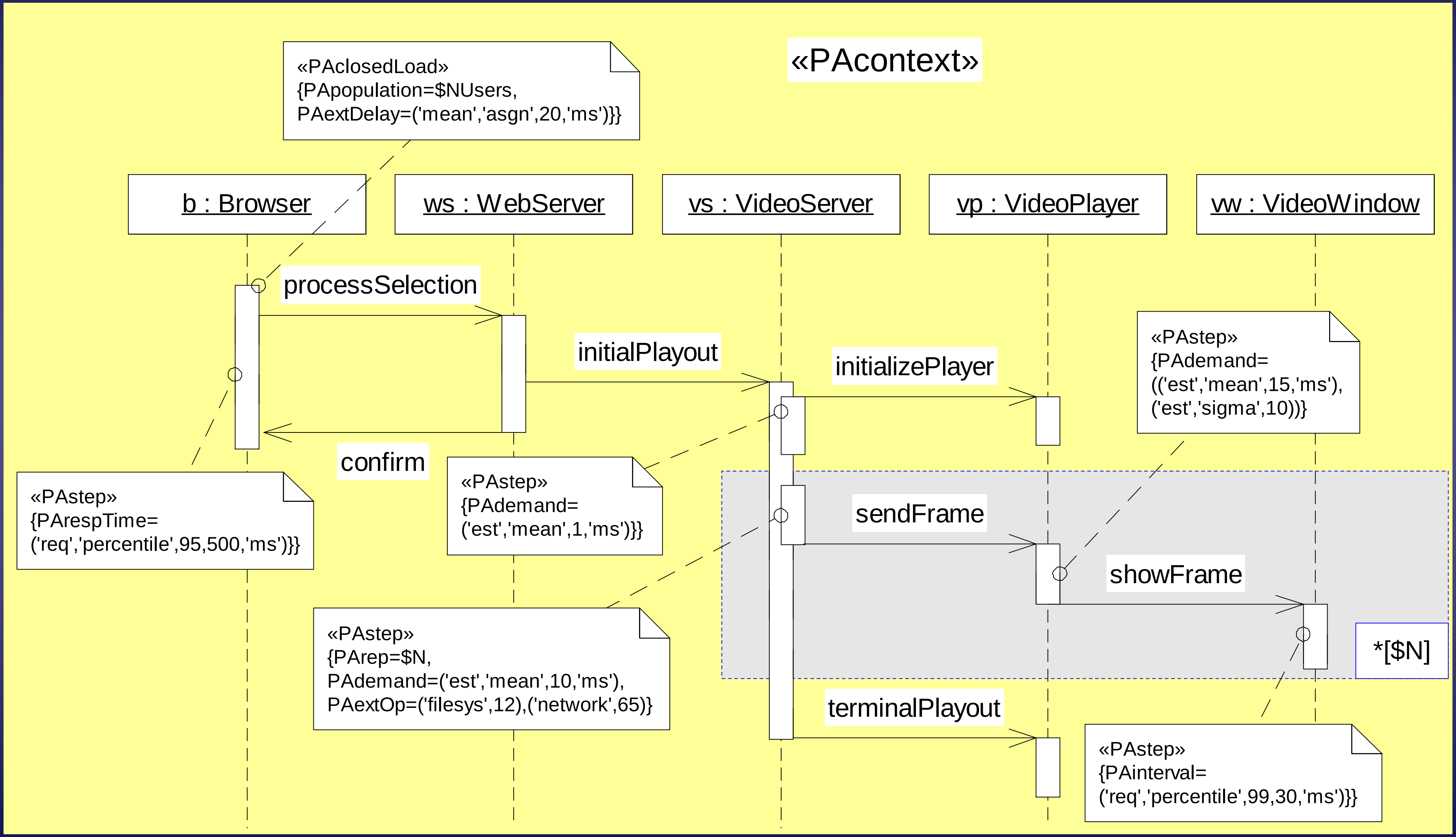
Usage Scenario



Example: Performance Requirements

- Estimated video server processing demand per frame = 10 ms
- Estimated viewer processing demand per frame = 15 ms (dev = 20 ms)
- Assumed network delay distribution: exponential with mean = 10 ms
- Measured packets per frame (LAN) = 65
- Measured video server file operations per frame = 12
- Max. number of concurrent users = $Nusers
- Average inter-session times = 20 minutes
- Frames in a video $N
- Video frame intervval = 30 ms
- Required confirmation delay: 95% < 500 ms
- Required interval between frame displays = 99% < 30 ms

Example: Annotations for a Scenario



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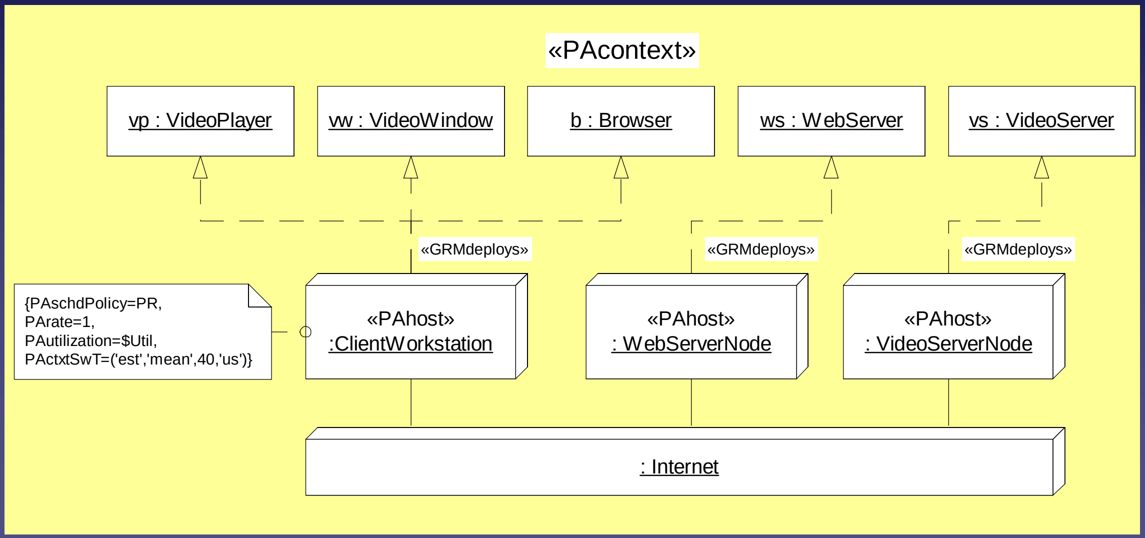
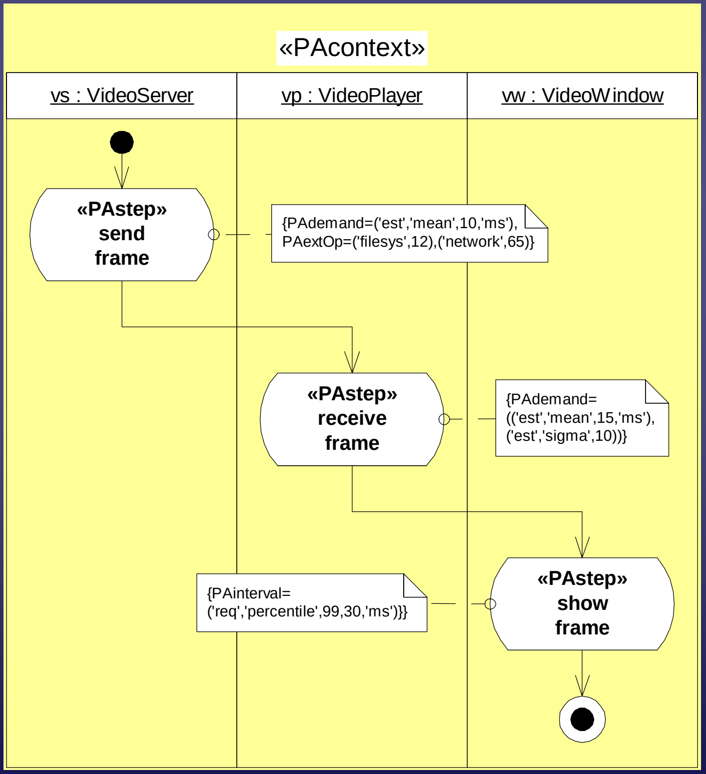
Example: More Annotations





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Defined Stereotypes (1 of 2)

Stereotype	Applies To	Tags	Description
«PAclosedLoad»	Action, ActionExecution, Stimulus, Action, Message, Method…	PArespTime [0..*] PApriority [0..1] PApopulation [0..1] PAextDelay [0..1]	A closed workload
«PAcontext»	Collaboration, CollaborationInstanceSet, ActivityGraph		A performance analysis context
«PAhost»	Classifier, Node, ClassifierRole, Instance, Partition	PAutilization [0..*] PAschdPolicy [0..1] PArate [0..1] PActxtSwT [0..1] PAprioRange [0..1] PApreemptible [0..1] PAthroughput [0..1]	A deferred receive
«PAopenLoad»	Action, ActionExecution, Stimulus, Action, Message, Method…	PArespTime [0..*] PApriority [0..1] PAoccurrence [0..1]	An open workload

Defined Stereotypes (2 of 2)

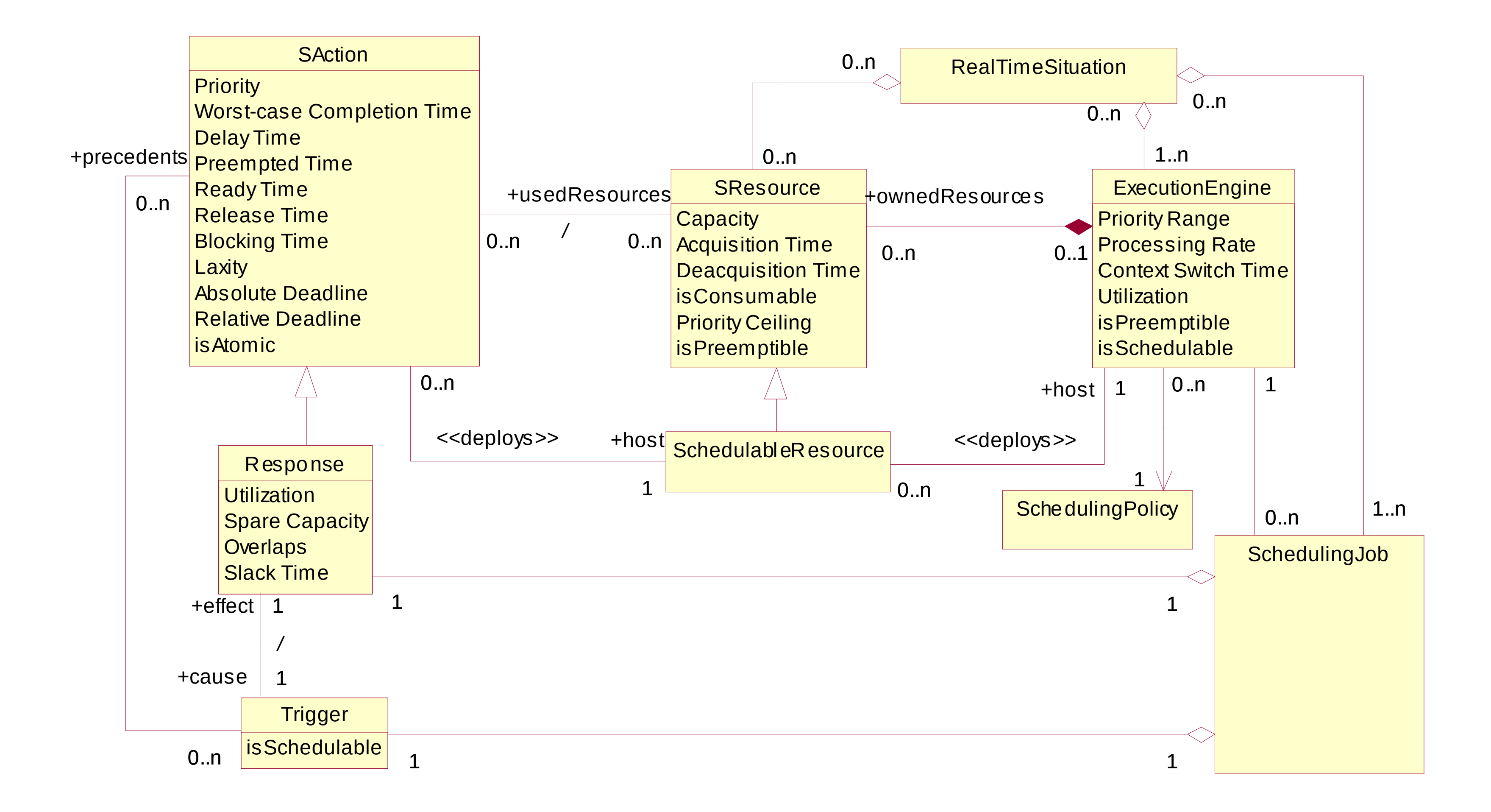
Stereotype	Applies To	Tags	Description
«PAresource»	Classifier, Node, ClassifierRole, Instance, Partition	PAutilization [0..*] PAschdPolicy [0..1] PAcapacity [0..1] PAmaxTime [0..1] PArespTime [0..1] PAwaitTime [0..1] PAthroughput [0..1]	A passive resource
«PAstep»	Message, ActionState, Stimulus, SubactivityState	PAdemand [0..1] PArespTime [0..1] PAprob [0..1] PArep [0..1] PAdelay [0..1] PAextOp [0..1] PAinterval [0..1]	A step in a scenario

Specifying Performance Values

- A complex structured string with the following format
  - <kind-of-value> , <modifier> , <time-value>
- Where:
  - <kind-of-value> ::= 'req' | 'assm' | 'pred' | 'msr'
  - Required, assumed, predicted, measured
  - <modifier> ::= 'mean' | 'sigma' | 'kth-mom' , <Integer> | 'max' | 'percentile' <Real> | 'dist'
  - E.g.:

{PAdemand = ('msr', 'mean', (20, 'ms'))}

Schedulability Analysis Sub-Profile

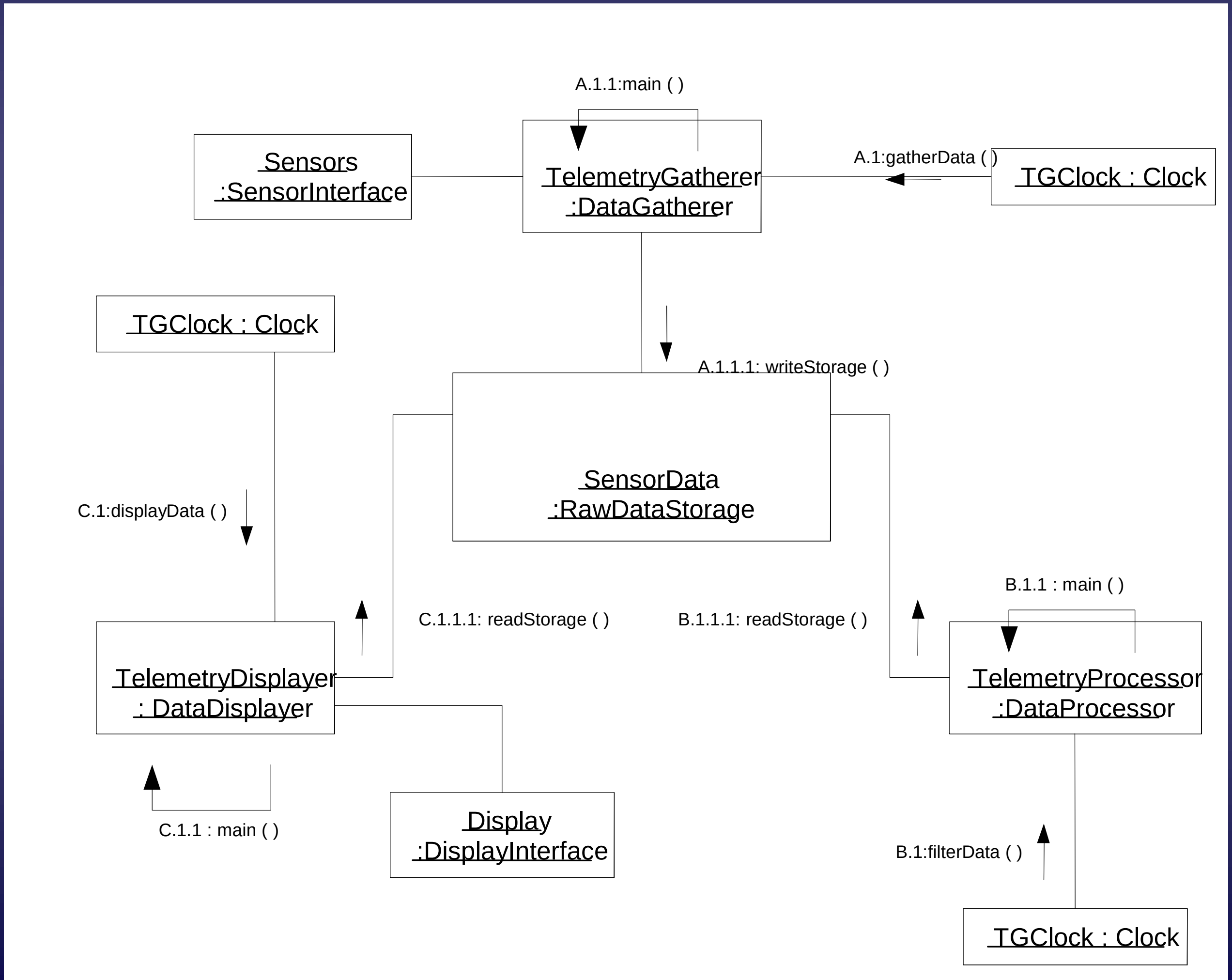


Policies Supported

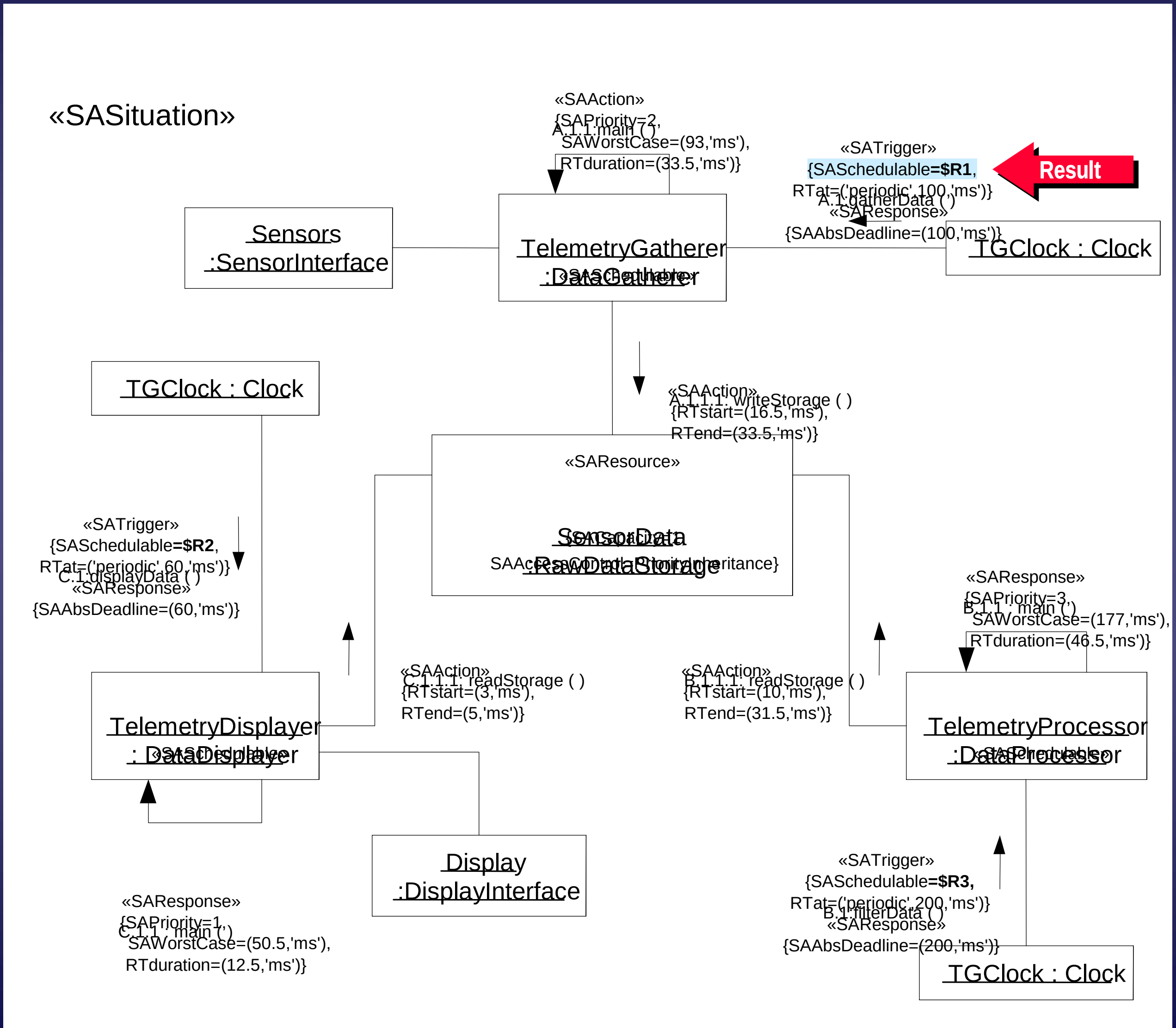
- Scheduling Policies:
  - Rate Monotonic, Deadline Monotonic, HKL, Fixed Priority, Minimum Laxity First, Maximize Accrued Utility, Minimum Slack Time
  - ...may be extended in the future
- Access Control Policies:
  - FIFO, Priority Inheritance, No Preemption, Highest Lockers, Priority Ceiling
  - ...may be extended in the future

Example

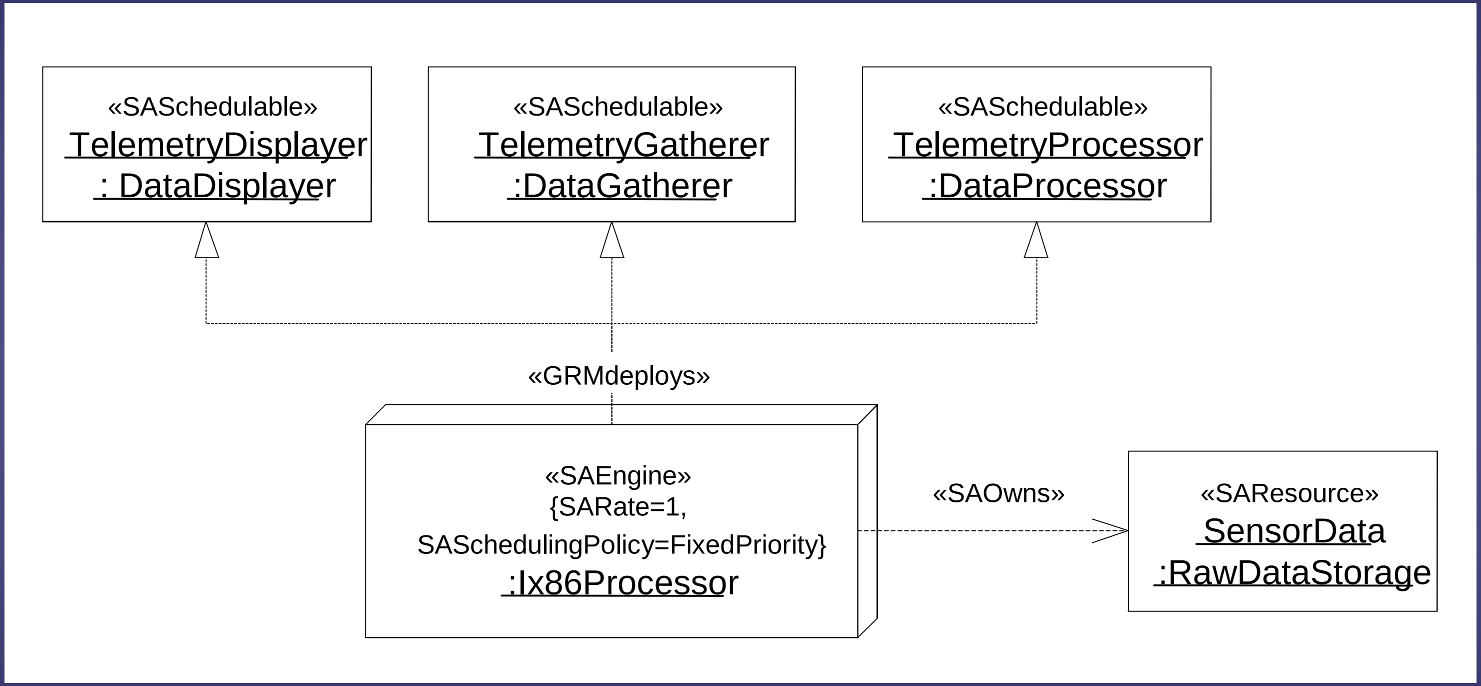
- A simple telemetry system with 3 cyclical tasks



Example: Schedulability Annotations

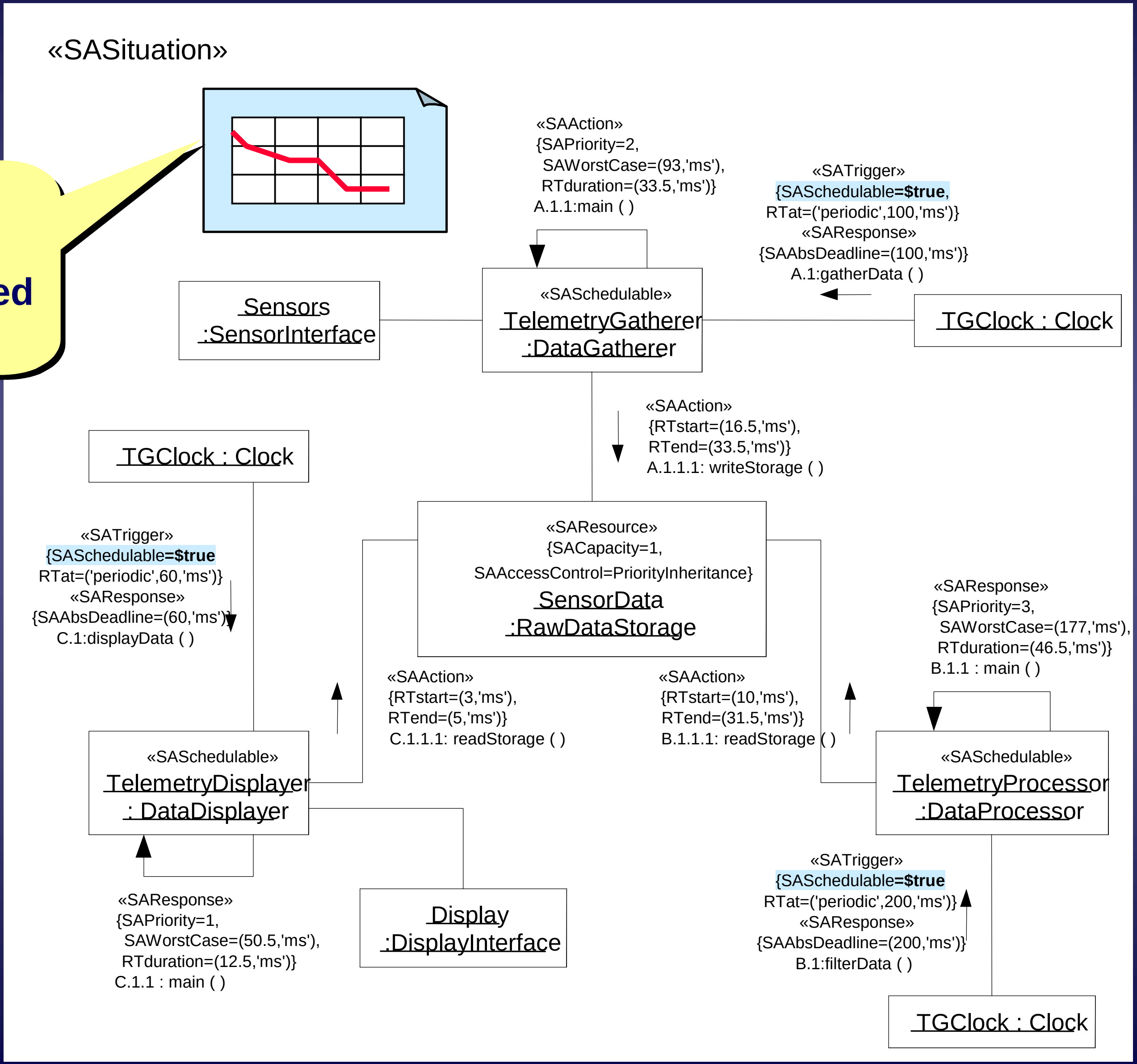


Example: Deployment Specification



Example: Analysis Results

Additional tool-specific results encased in UML Notes



Defined Stereotypes (1 of 3)

Stereotype	Applies To	Tags	Description
«SAAction» (subclass of «RTaction» and «CRAction»)	Action, ActionExecution, Stimulus, Action, Message, Method…	SAPriority [0..1] SAActualPty [0..1] SABlocking [0..1] SAReady [0..1] SADelay [0..1] SARelease [0..1] SAPreempted [0..1] SAWorstCase [0..1] SALaxity [0..1] SAPriority [0..1] SAAbsDeadline [0..1] SARelDeadline [0..1] SAusedResource [0..1] SAhost [0..1]	An action
«SAEngine»	Node, Instance, Object, Classifier, ClassifierRole	SASchedulingPolicy [0..1] SAAccessPolicy [0..1] SARate [0..1] SAContextSwitch [0..1] SAPriorityRange [0..1] SAPreemptible [0..1] SAUtilization [0..1] SASchedulable [0..1] Saresources [0..1]	An execution engine

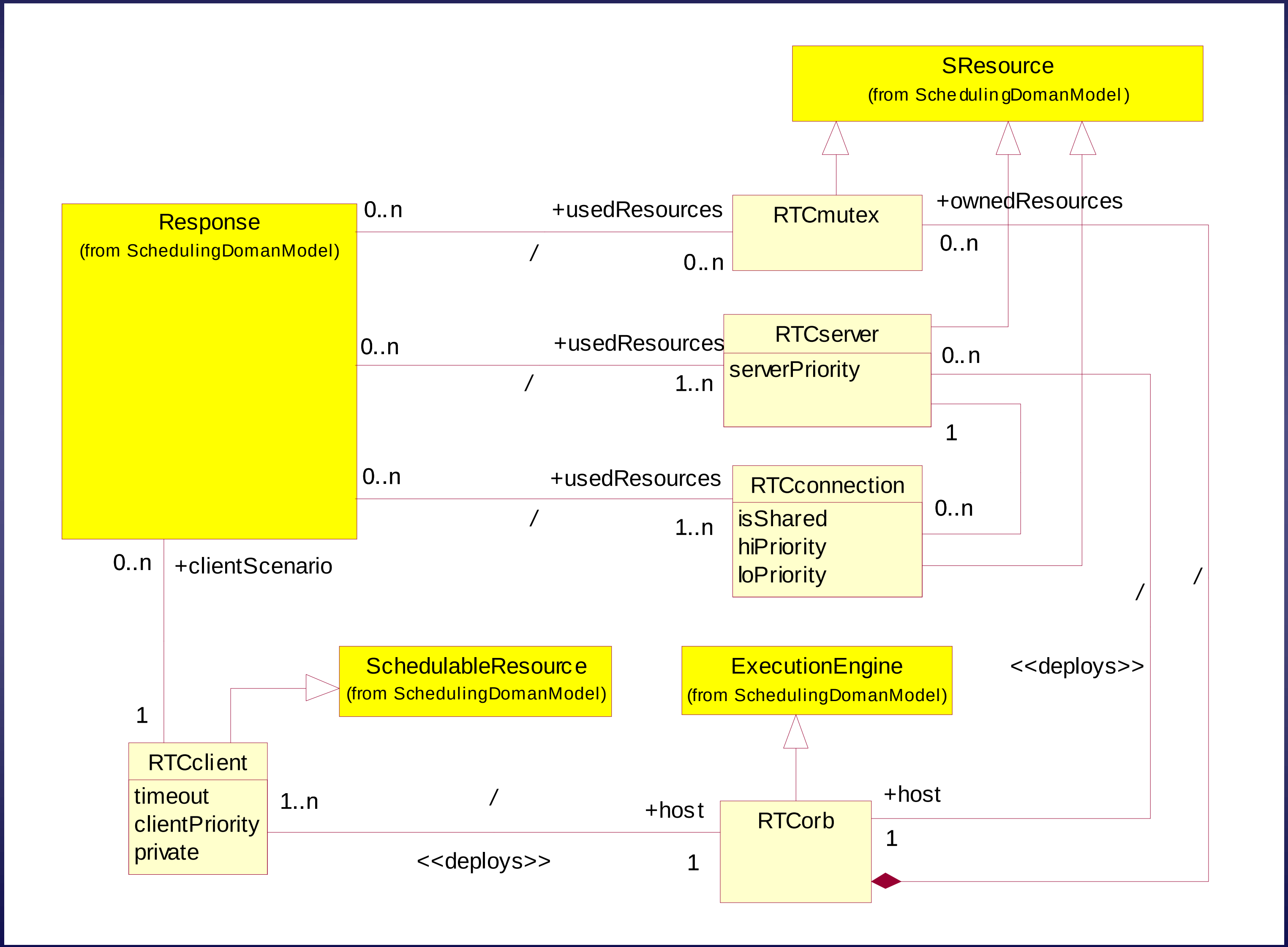
Defined Stereotypes (2 of 3)

Stereotype	Applies To	Tags	Description
«SAOwns» (subclass of «GRMrealize»)	Abstraction		Identifies ownership of resources
«SAPrecedes»	Usage		A precedence relationship between actions and triggers
«SAResource»	Classifier, ClassifierRole, Instance, Object, Node	SAAccessControl [0..1] SAConsumable [0..1] SACapacity [0..1] SAAcquisition [0..1] SADeacquisition [0..1] SAPtyCeiling [0..1] SAPreemptible [0..1]	A resource of some kind
«SAResponse» (subclass of «SAAction»)	Action, ActionExecution, Stimulus, Action, Message, Method…	SAUtilization [0..1] SASpare [0..1] SASlack [0..1] SAOverlaps [0..1]	A response to a stimulus or action
«SASchedulable» (subclass of «SAResource»)	Classifier, ClassifierRole, Instance, Object, Node		A schedulable resource

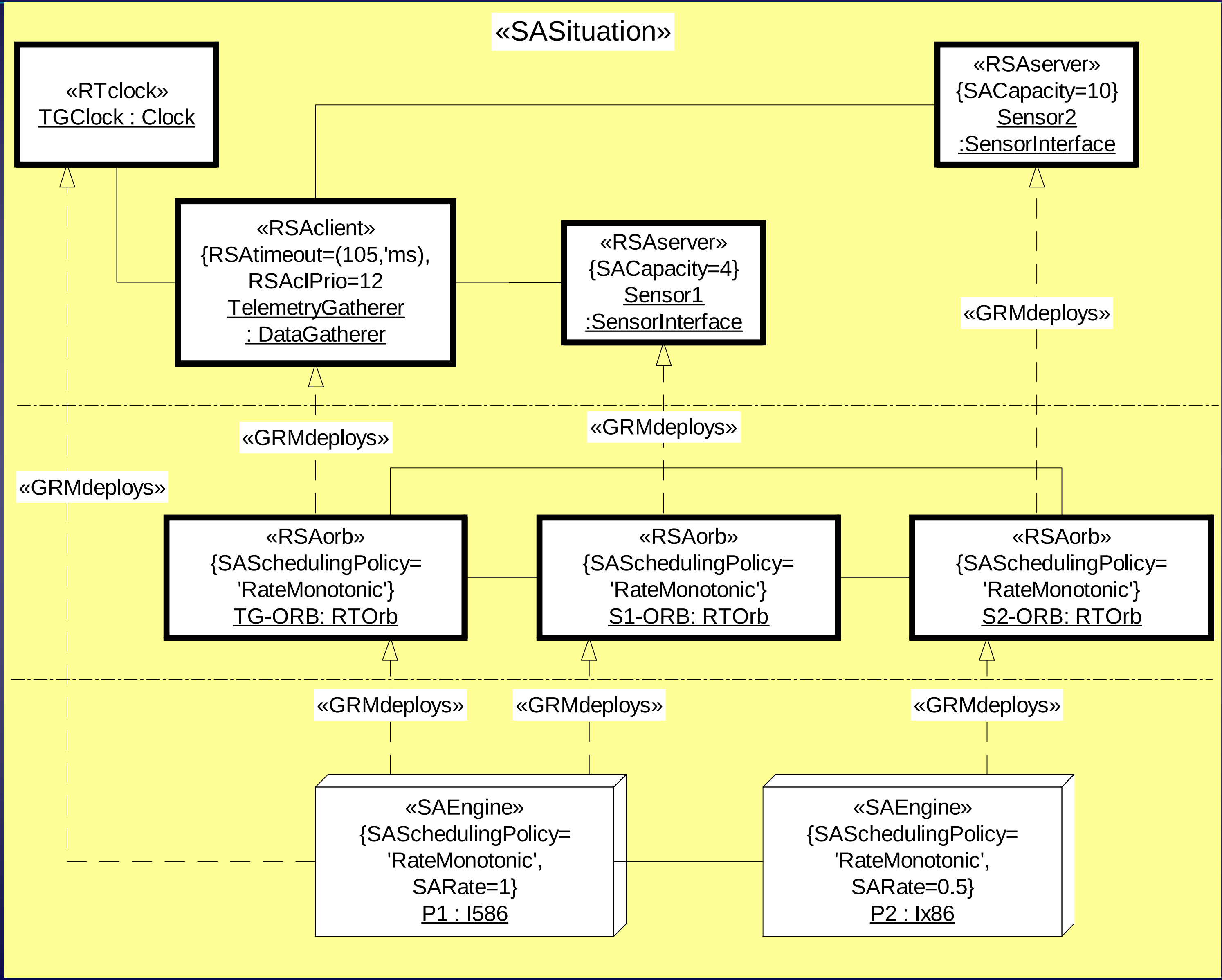
Defined Stereotypes (3 of 3)

Stereotype	Applies To	Tags	Description
«SAScheduler»	Classifier, ClassifierRole, Instance, Object	SASchedulingPolicy [0..1] SAExecutionEngine [0..1]	A scheduler
«SAPrecedes»	Usage		A precedence relationship between actions and triggers
«SASituation»	Collaboration, CollaborationInstance, ActivityGraph		A schedulability analysis context
«SATrigger» (subclass of «SAAction»)	Message, Stimulus	SASchedulable [0..1] SASAprecedents [0..1]	A trigger
«SAusedHost»	Usage		Identifies schedulable resources used for execution of actions
«SAUses»	Usage		Identifies sharable resources

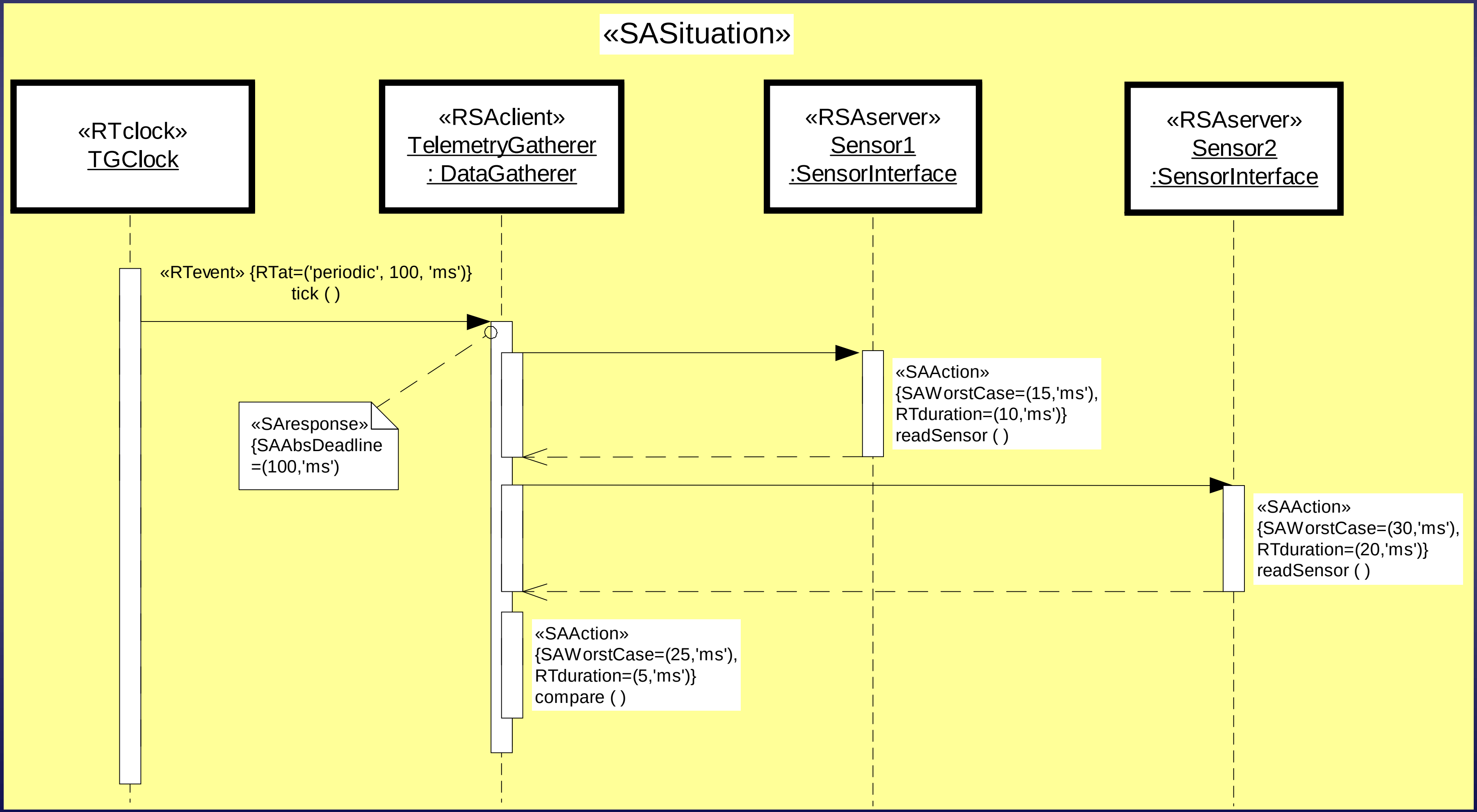
Real-Time CORBA: Schedulability Sub-Profile



Example: RT CORBA



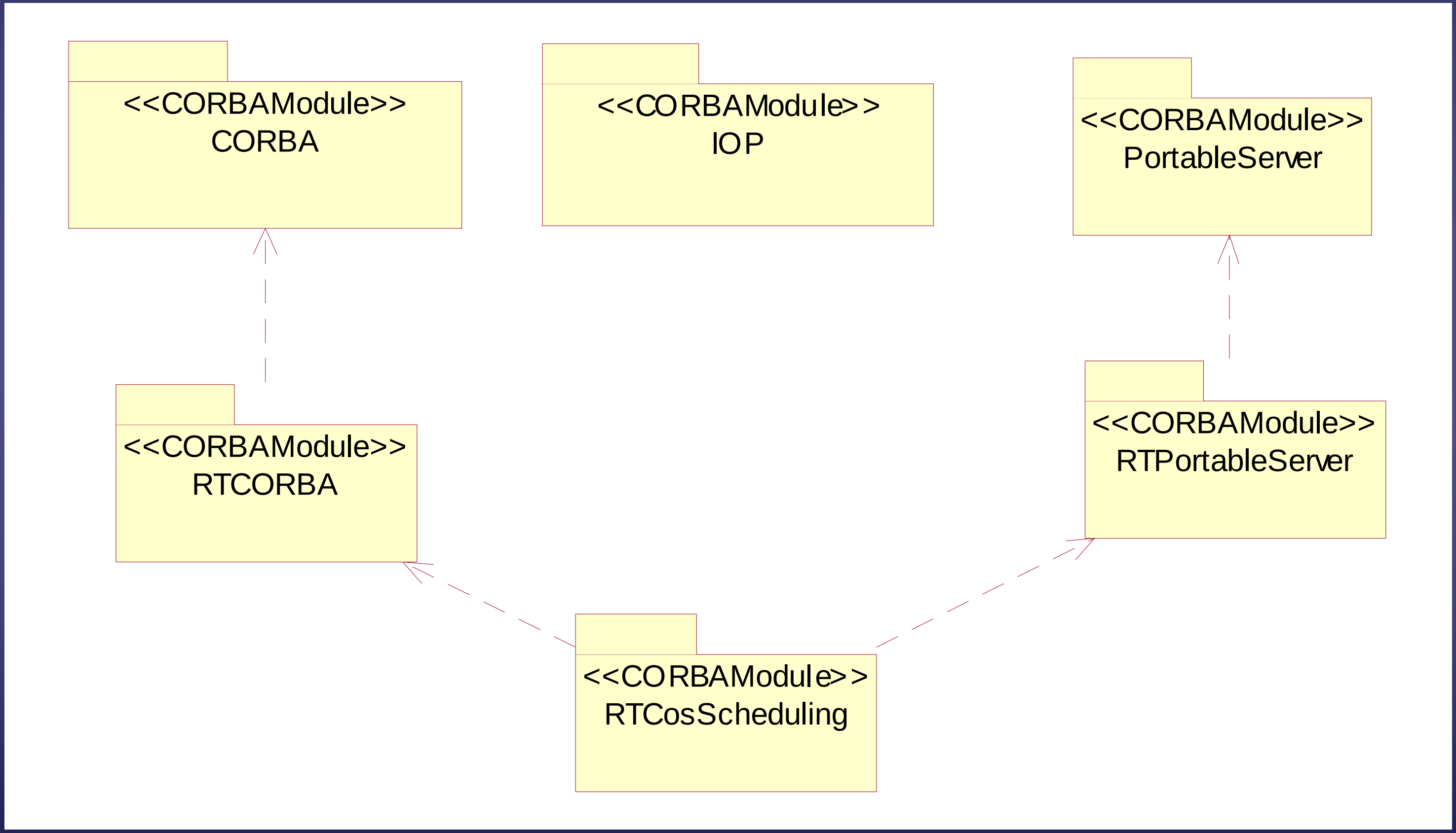
Example: RT CORBA Usage Scenario



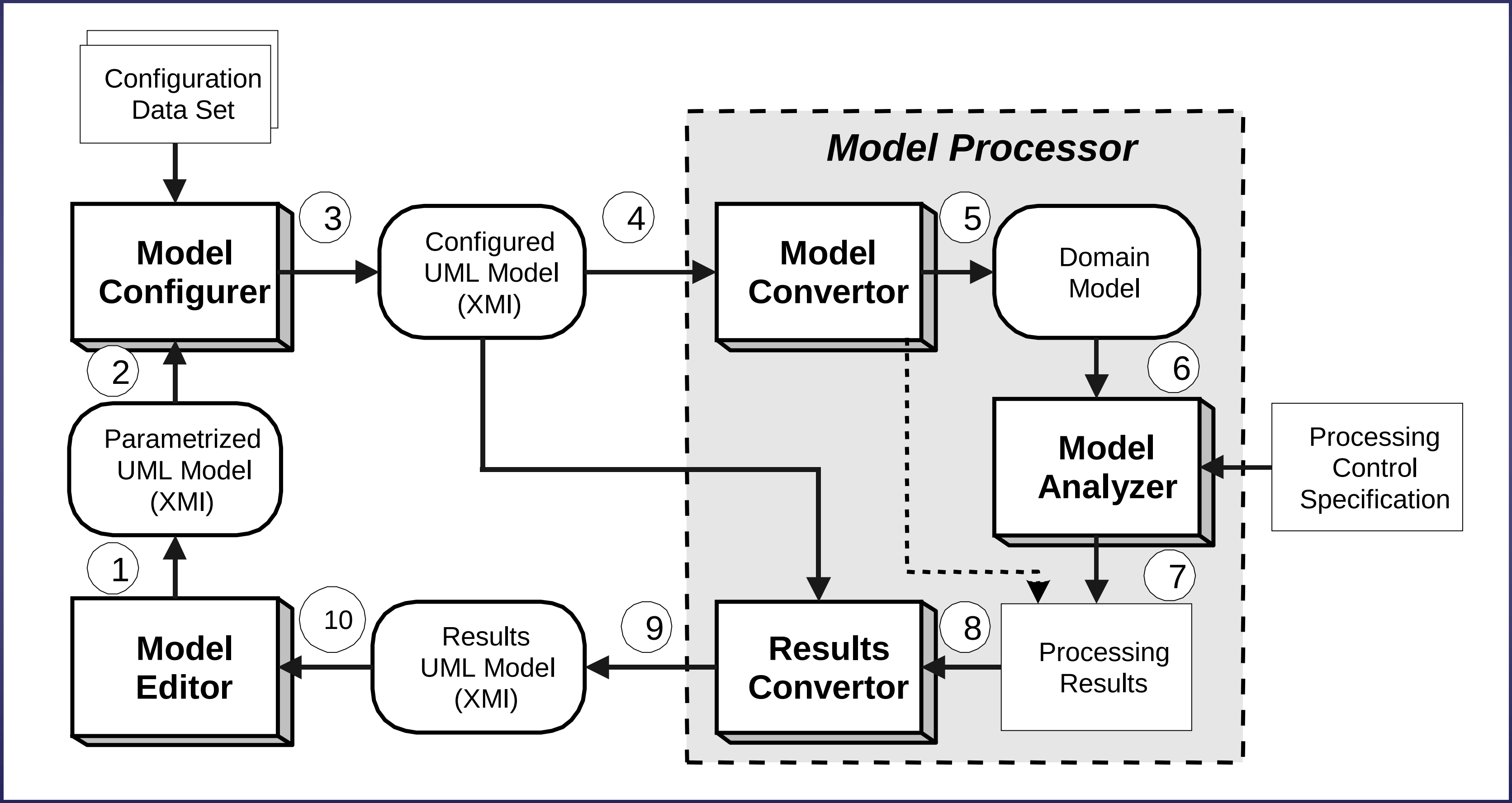
Defined Stereotypes

Stereotype	Applies To	Tags	Description
«RSAclient» (subclass of «SASchedulable»)	Classifier, ClassifierRole, Instance, Object, Node	RSAtimeout [0..1] RSAclPrio [0..1] RSAprivate [0..1] RSAhost [0..1]	An RT CORBA client
«RSAconnection» (subclass of «SASchedulable» and «SAResource»)	Classifier, ClassifierRole, Instance, Object, Node	SAAccessControl [0..1] RSAshared [0..1] RSAhiPrio [0..1] RSAloPrio [0..1] RSAserver [0..1]	An RT CORBA connection
«RSAmutex» (subclass of «SAResource»)	Classifier, ClassifierRole, Instance, Object, Node	SAAccessControl [0..1] RSAhost [0..1]	An RT CORBA mutex
«RSAorb» (subclass of «SAResource»)	Classifier, ClassifierRole, Instance, Object, Node	SAschedulingPolicy [0..1]	An RT CORBA ORB
«RSAserver» (subclass of «SAResource»)	Classifier, ClassifierRole, Instance, Object, Node	RSAsrvPrio [0..1] SACapacity [0..1]	An RT CORBA server

Real Time CORBA: Infrastructure Model



Model Processing Paradigm and Tools



The Tag Value Language

- Tagged value format:

  {<tag-name> = <tag-value>}

- Used to specify complex (structured) tagged values
- Based on a small proper subset of the freeware Perl language
  - Includes: variables, numbers, booleans, strings, lists, expressions (including conditionals), operators, and functions
- Suitable for:
  - expressing complex dependencies between values
  - writing processing scripts

Summary: The Real Time UML Profile

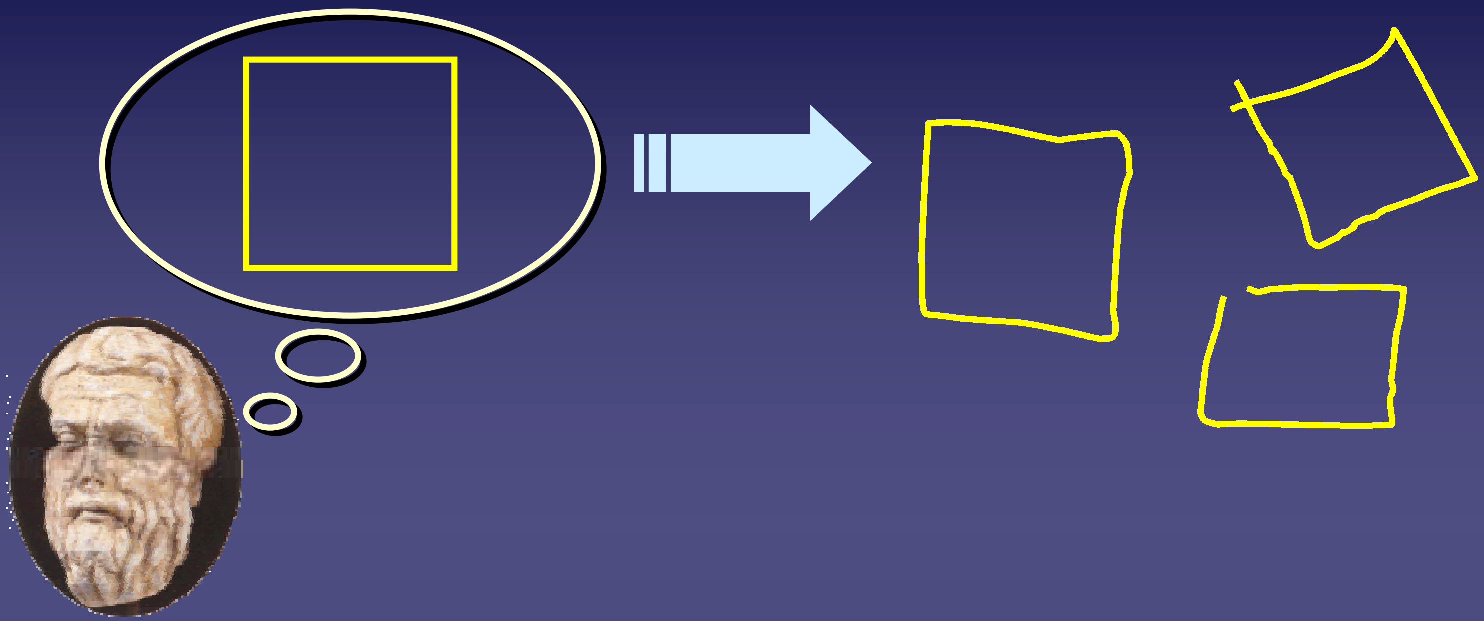
- The RT UML Profile defines a set of extensions for directly expressing real-time domain concepts in UML:
  - resources
  - concurrency mechanisms
  - time and timing mechanisms
- Furthermore, it allows the specification of quantitative aspects in the same models such that the models can be analyzed
  - predictive models that can be used to validate (risky) design approaches before major investments are made

- Real-Time Systems and the Object Paradigm
  - Real-Time System Essentials
  - Essentials of the Object Paradigm
- UML as a Real-Time Modeling Language
- The Real-Time UML Profile
- Engineering-Oriented Design of Real-Time Systems
- Summary and Conclusions

Common Wisdom...

- When designing software, we are instructed to ignore details of the technology and similar "implementation" issues until we have a sound logical solution to the problem
  - simplifies the design problem (separation of concerns)
  - software is portable to new/different technologies
- But, what about real-time systems?

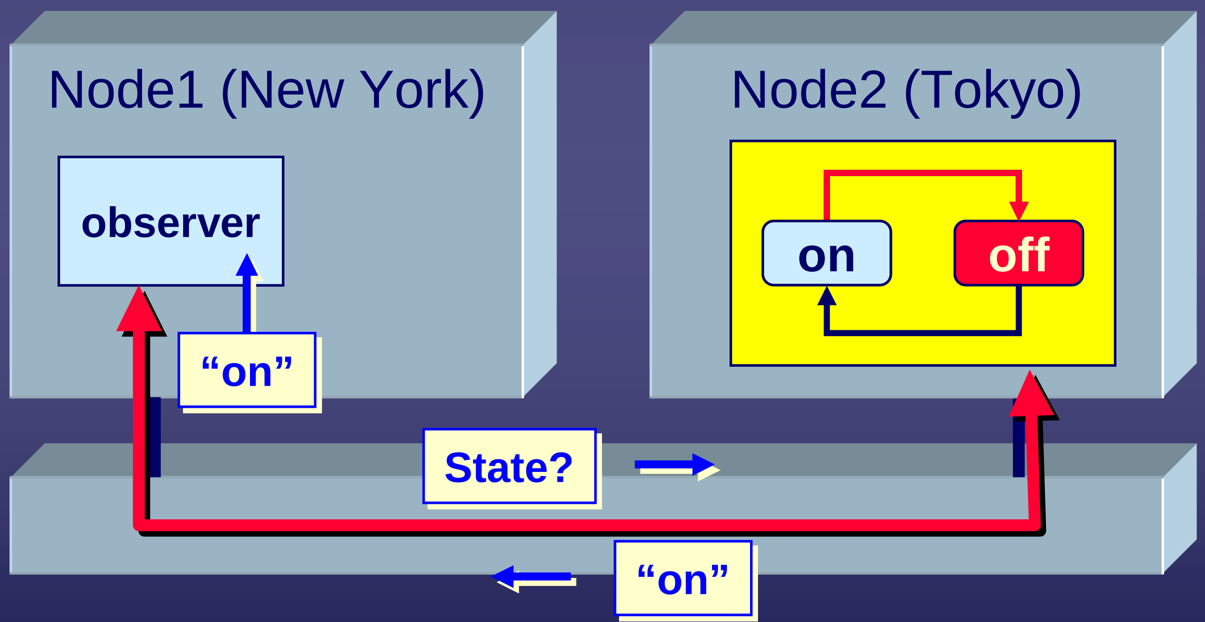
The Ideal and the Real



- The idealized “forms” of pure logic acquire the finite characteristics of the physical stuff out of which they are spun
  - limited speed, limited capacity, limited availability,...

Real System Design Issues (1)

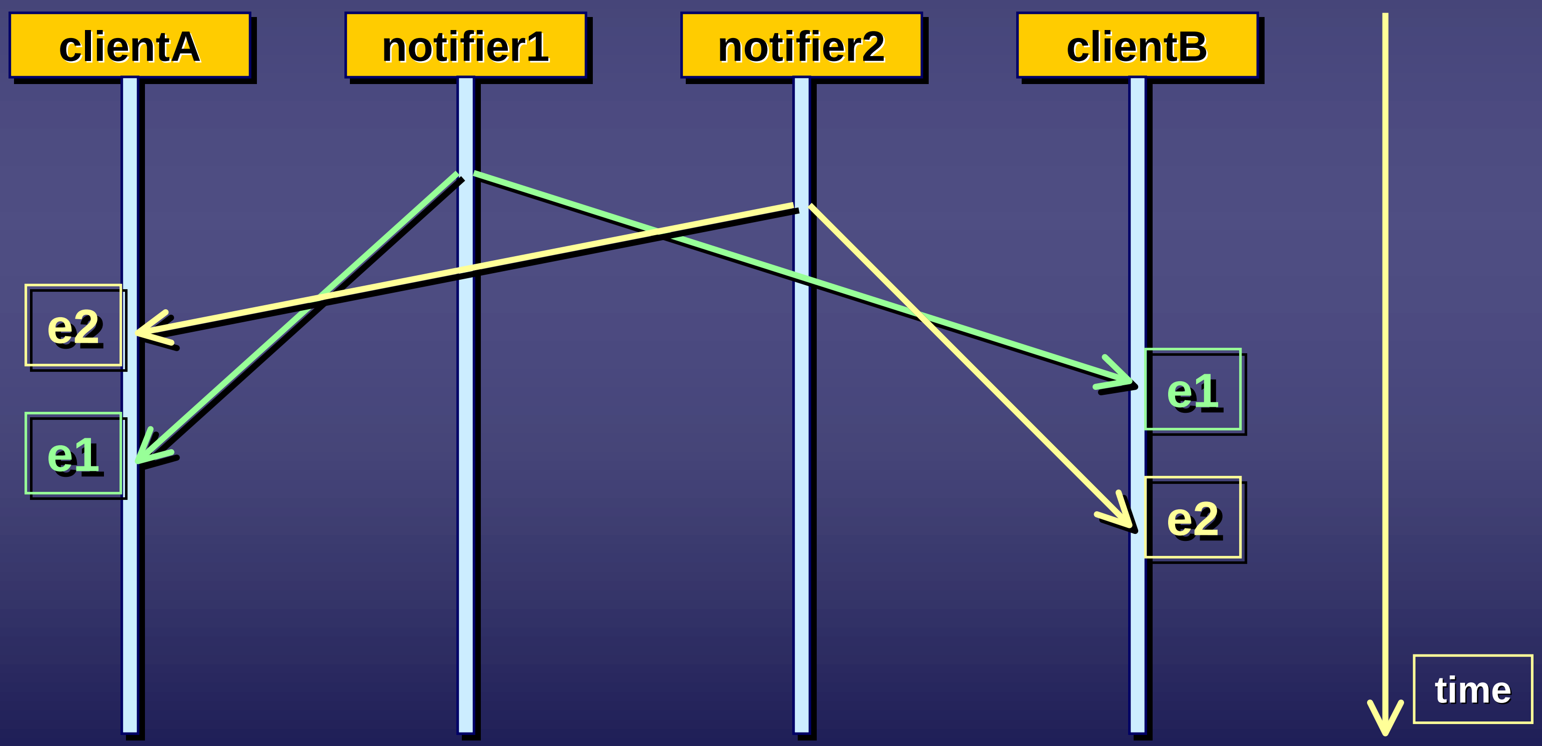
- Possibility of out-of-date state information due to lengthy (and variable) transmission delays



It's a game of numbers!

Real System Design Issues (2)

- Inconsistent views of system state:
  - different observers see different event orderings



It’s a game of numbers!

Distributed System Characteristics

- Key characteristics:
  - concurrency and asynchrony
  - need for communication and synchronization between sites
  - communication delays
  - possibility of partial failure
- Each of these adds significant “weight” to the programming problem
- *Distributed programming is different from and much more complex than conventional programming*

Real-World Real-Time Design Issues

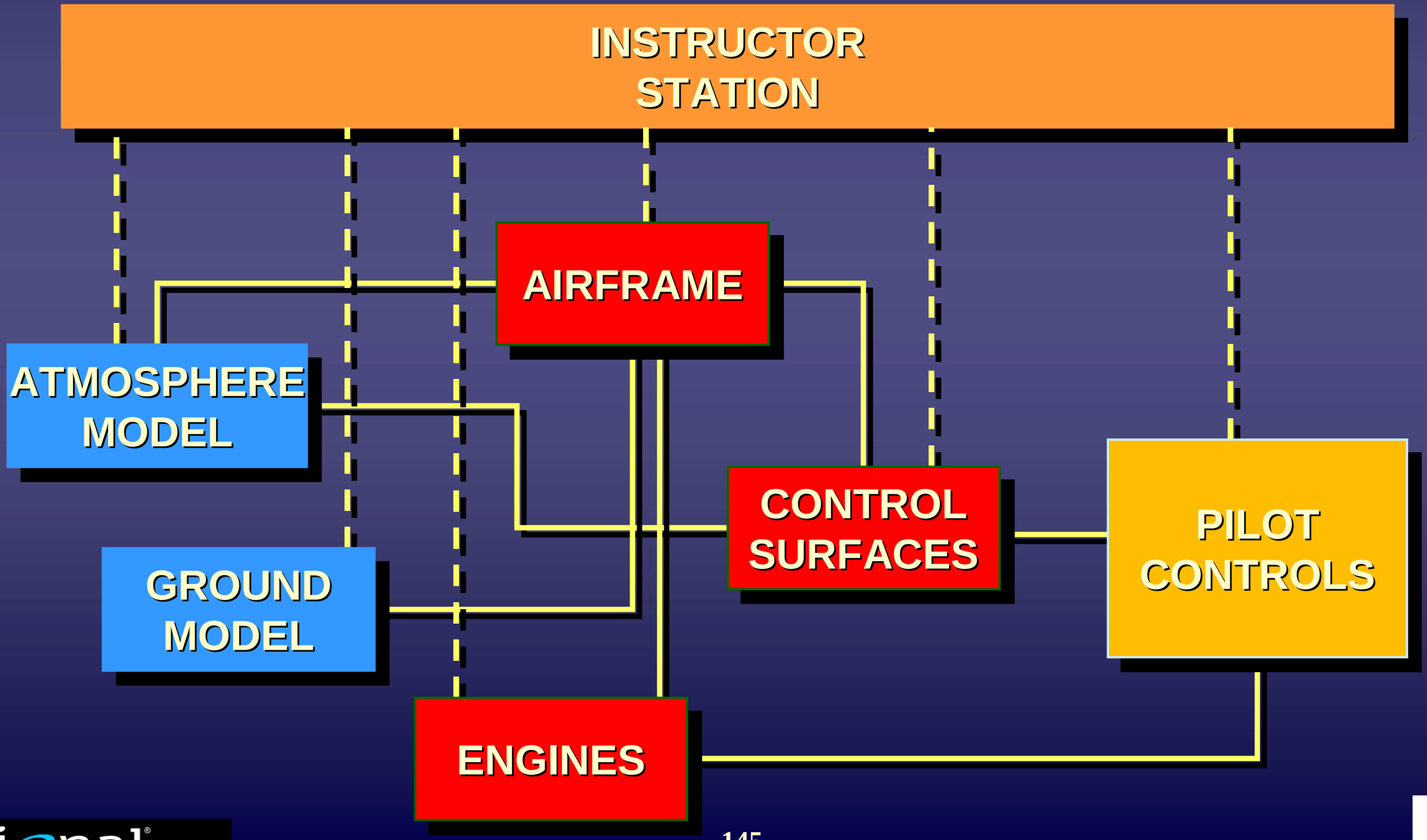
- Much of the complexity associated with these systems is the result of the “intrusion” of the inherently complex physical world into the idealized logical world of software

- *The real-time design dilemma:*

  if the physical world intrudes on the logical world, how can we separate the “logical” world of design from the “physical” world of implementation to achieve portability?

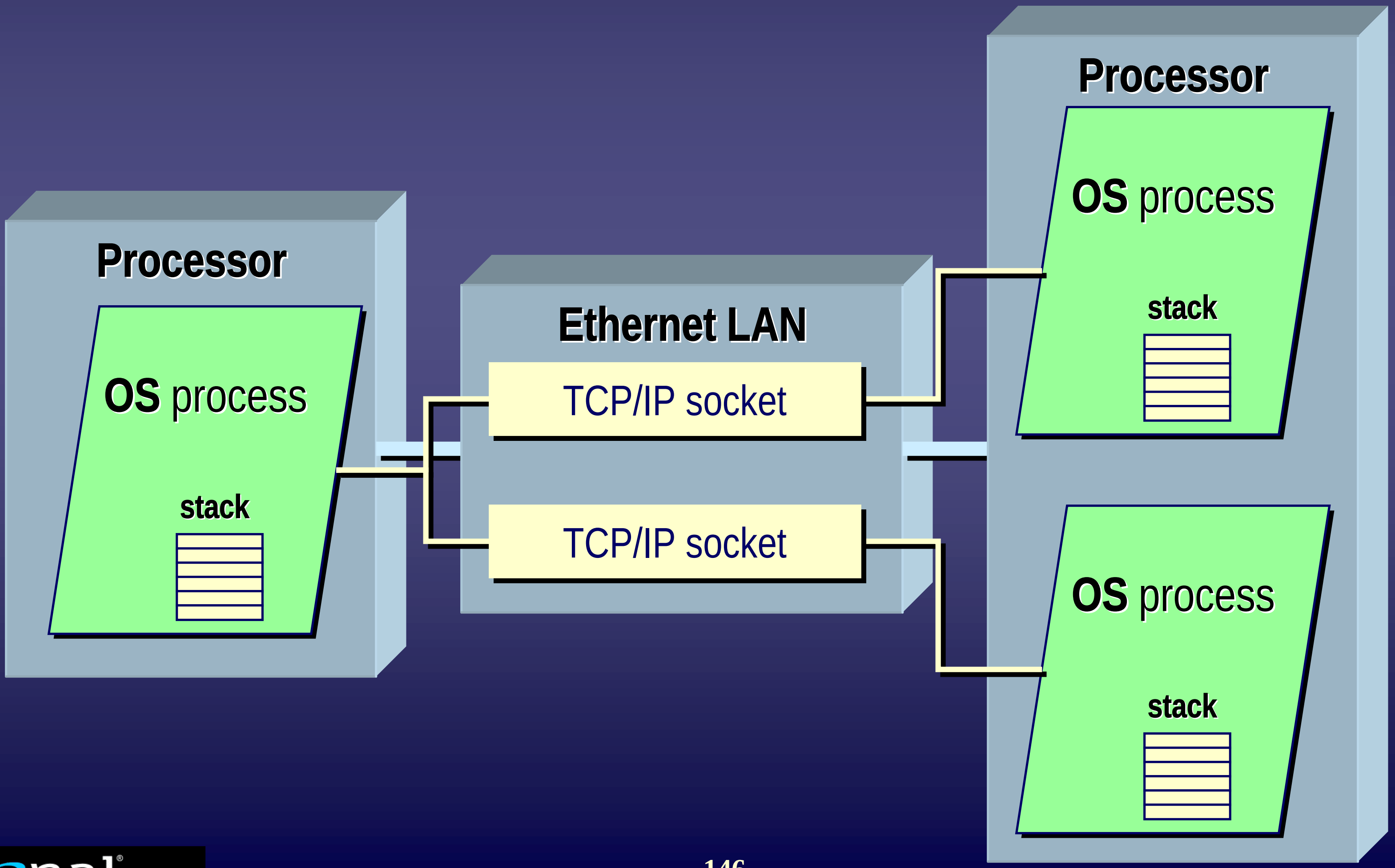
Logical (Conceptual) Viewpoint

- A technology-independent view of the software
  - a "virtual" mechanism realized by a computer

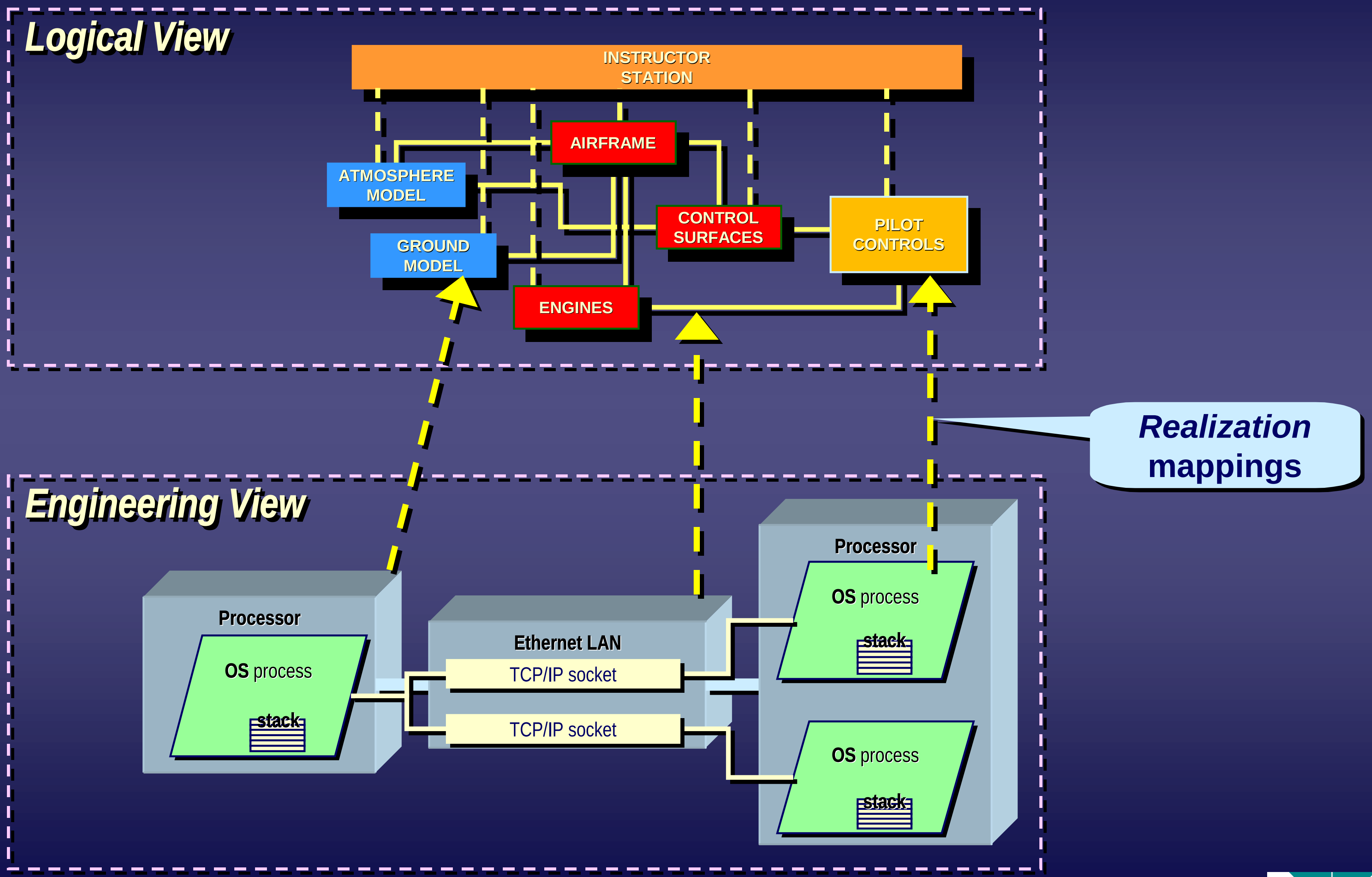


Engineering (Realization) Viewpoint

- The realization of a specific set of logical components using facilities of the run-time environment

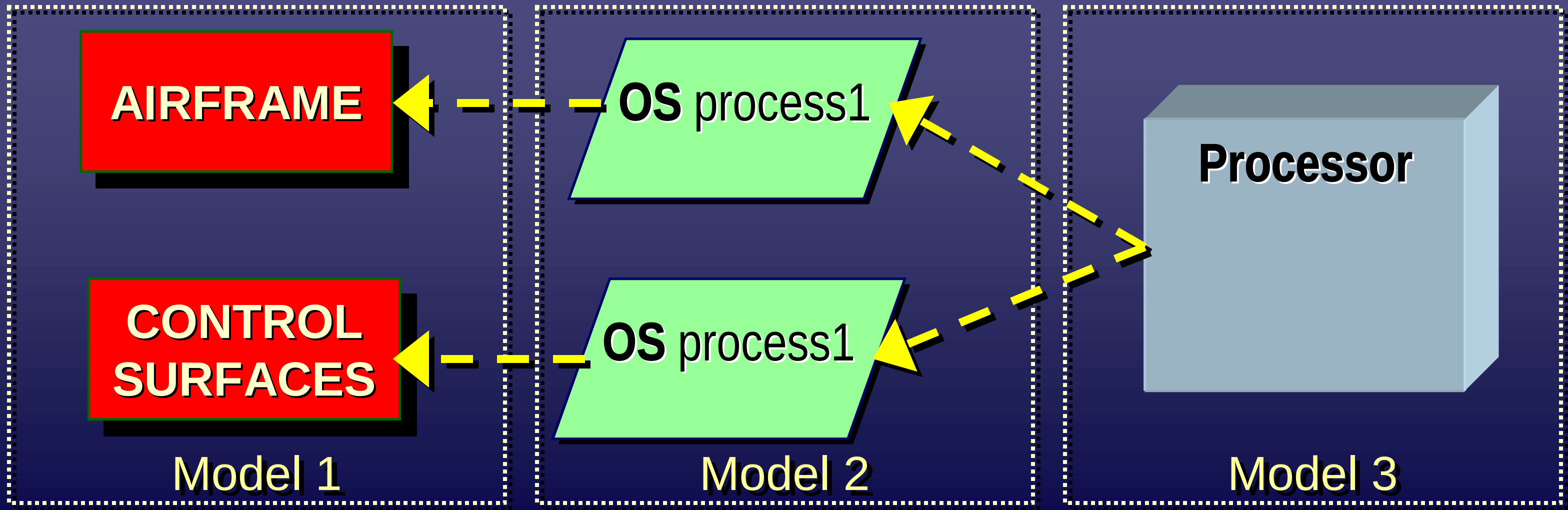


Views and Mappings



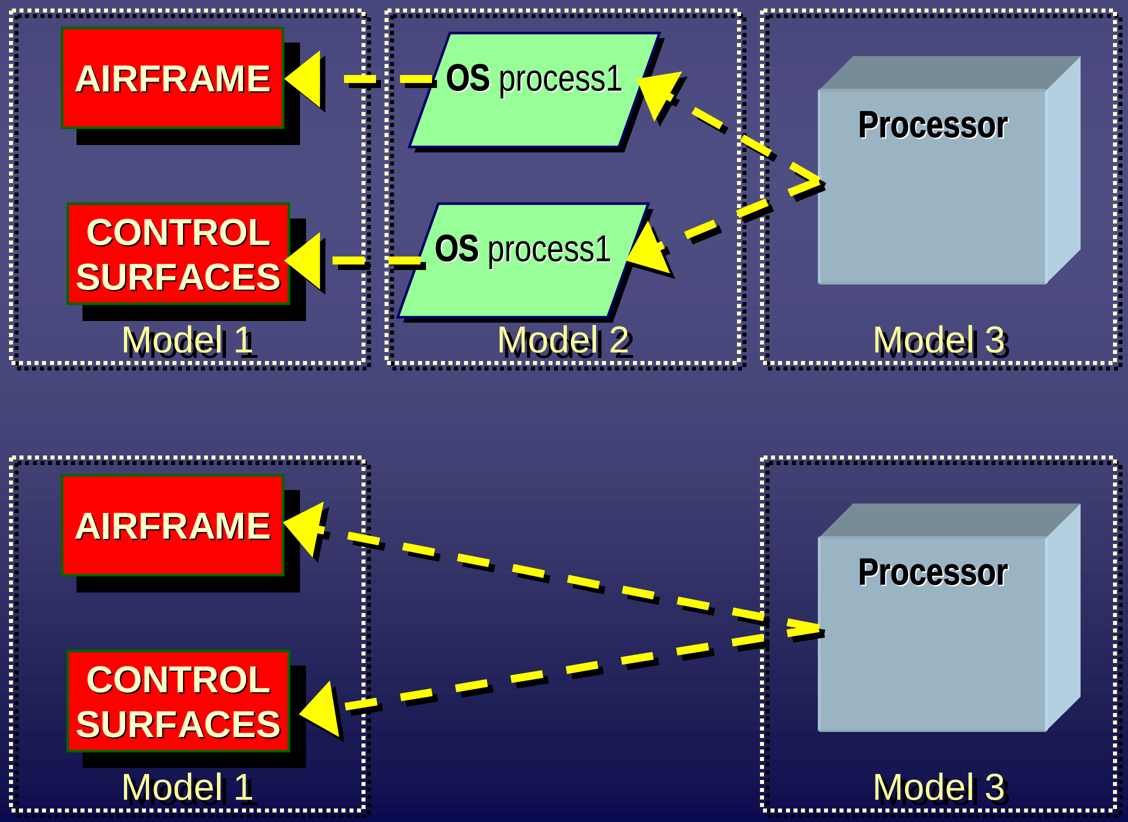
Realization Mappings

- A correspondence between elements of two distinct models (logical and engineering)
- Semantics: the logical elements are *implemented* by the corresponding engineering model elements
  - logical elements can be viewed as “residing” on the corresponding engineering elements



Selecting a Level of Abstraction

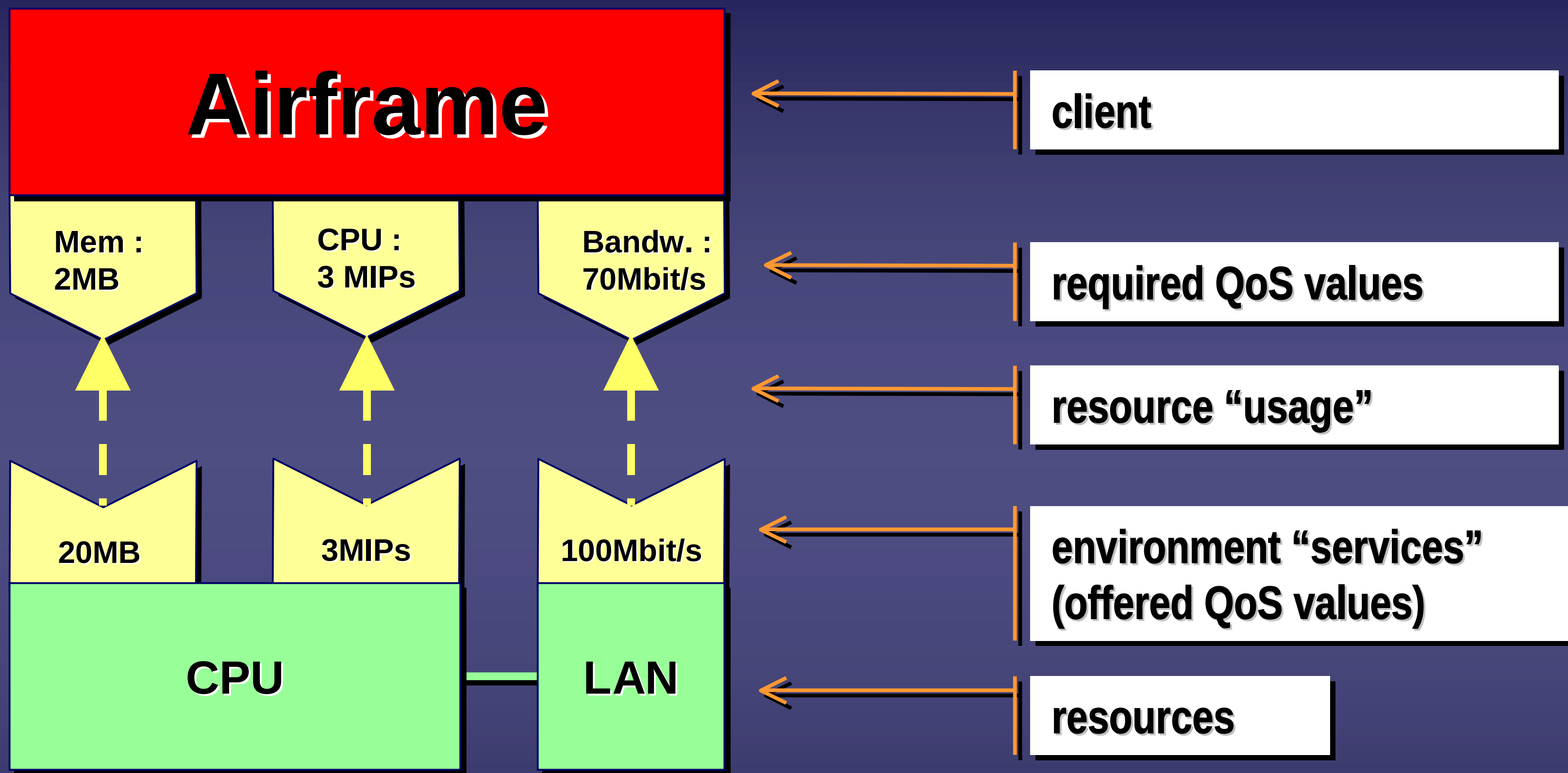
- Intermediate levels may be abstracted out
  - depends on the desired granularity of modeling
  - affects the semantics of the realization relationship



The Engineering Viewpoint in RT Systems

- The engineering view represents the “raw material” out of which we construct the logical view
  - the quality of the outcome is only as good as the quality of the ingredients that are put in
  - as in all true engineering, the quantitative aspects are often crucial (How <u>long</u> will it take? How <u>much</u> will be required?...)
- The ability to accurately model the relationship between the engineering and logical models is crucial to real-time system design
  - Unfortunately, UML deployment diagrams are inadequate

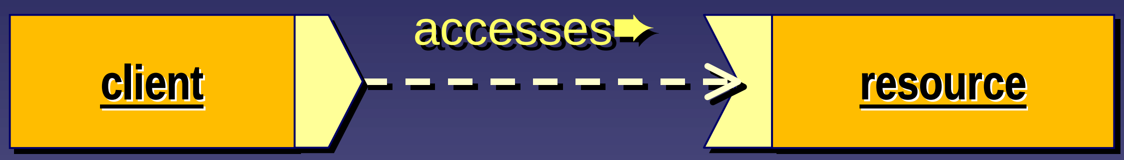
The Resource Model and Realization



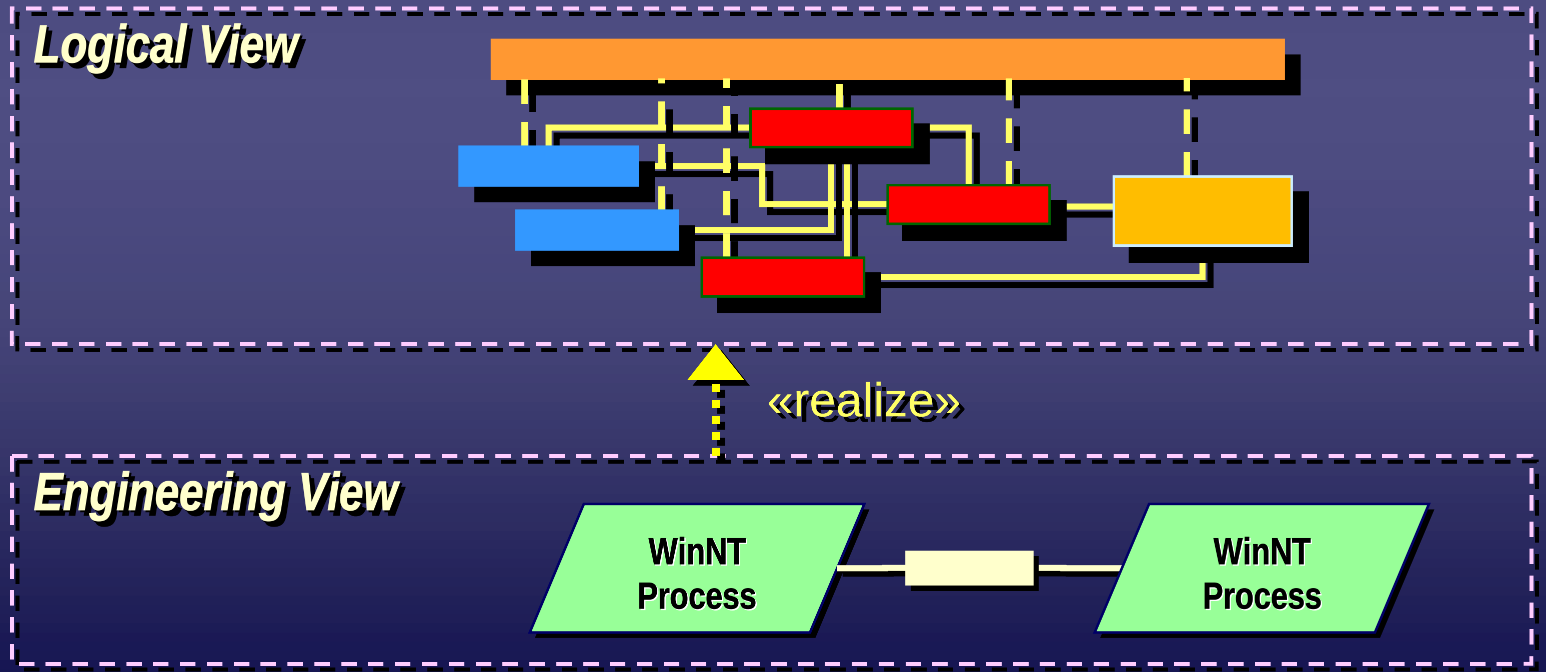
⇒*The same QoS framework can be used for quantifying realization relationships*

Two Interpretations of Resource Model

- The peer interpretation

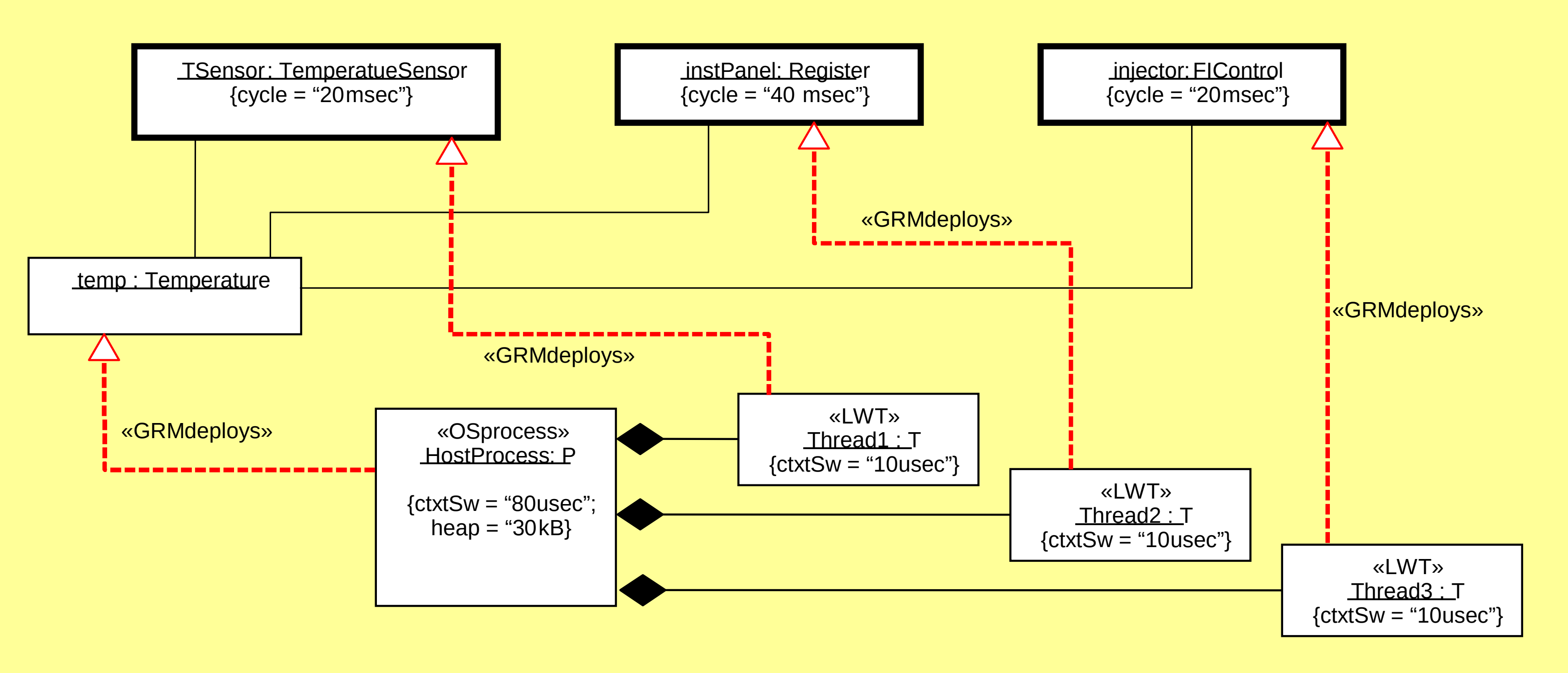


- The layered interpretation (the 2-viewpoint model)

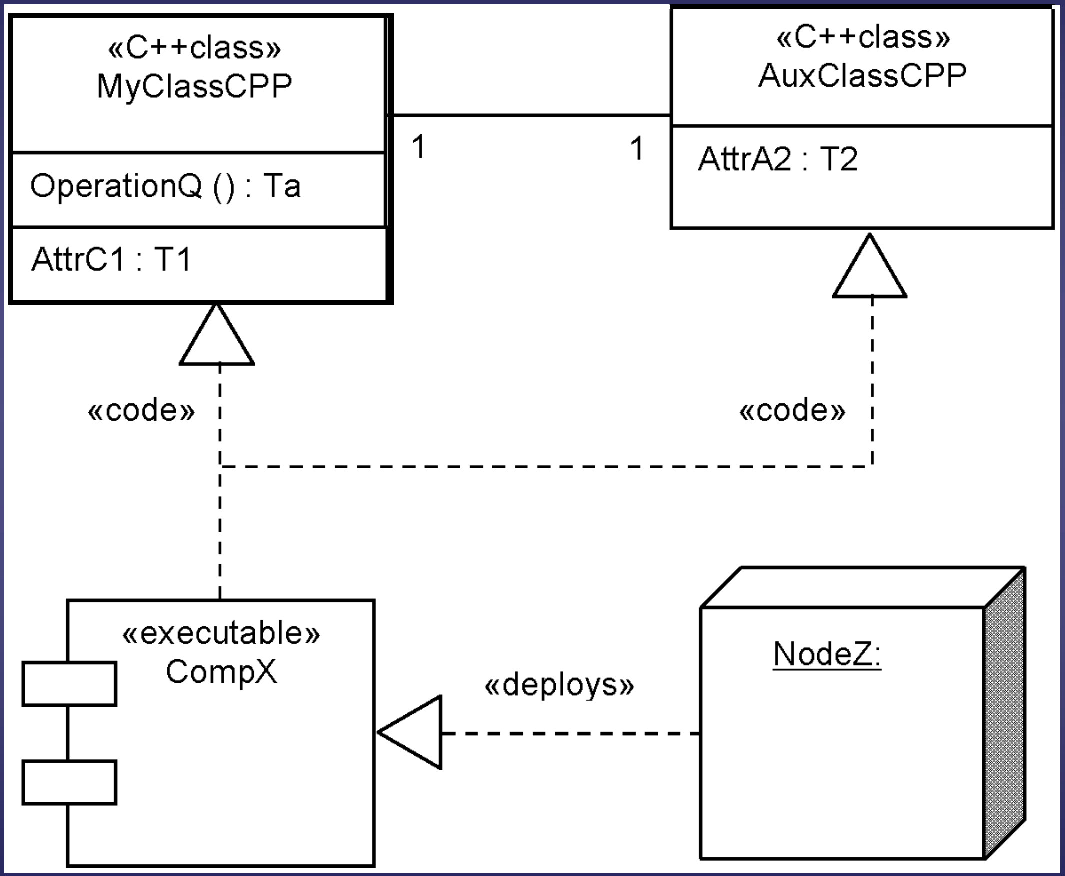


Example: Realization Relationships

- For sophisticated multi-layer deployment modeling

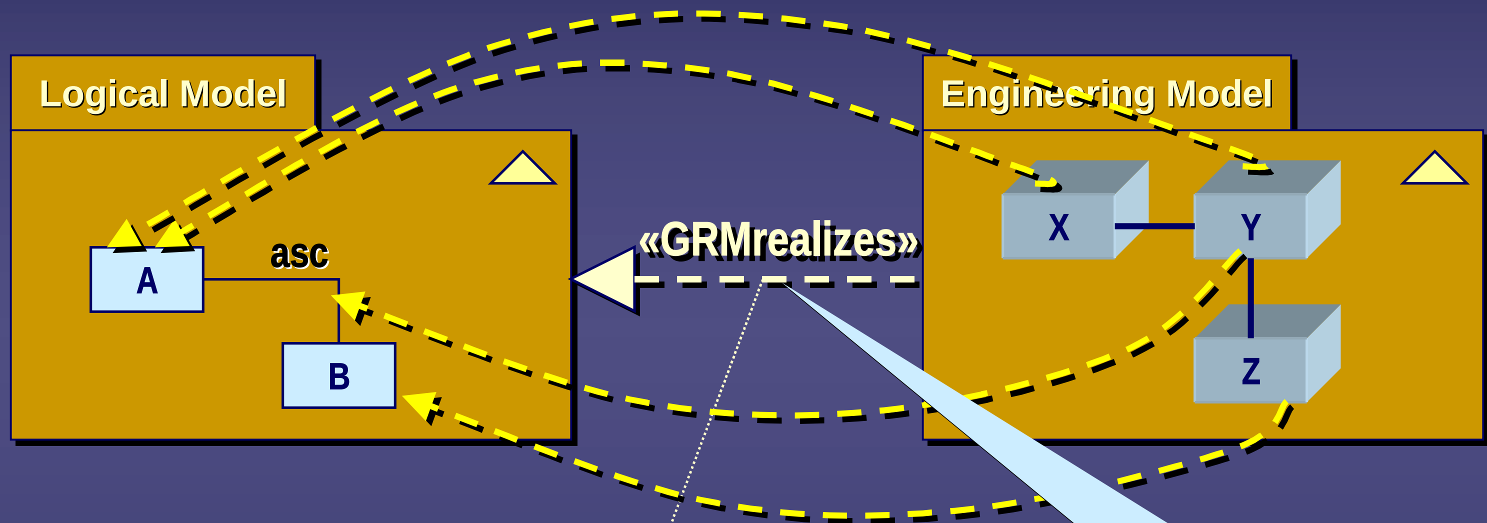


Forms of Realization



Modeling Realization in UML

- An association between models with explicit realization mappings between model elements



Source element	Dest. elements
A	X, Y
asc	Y
B	Z

Compact tabular form

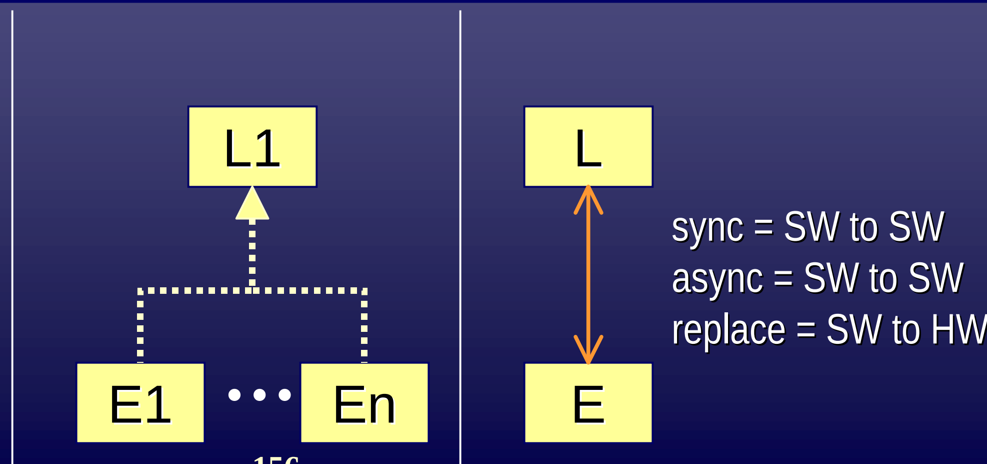
A stereotype of the UML realizes relationship

deployment table

Specifying Realization Mappings

- Captures the specifics of the realization mapping
  - Either as a string (tag value) or as a table

Logical Elements	Engineering Elements	Mode	Linkage	Additional Constraints
<List of logical model elements>	*<List of corresponding engineering model elements>*	*<If there are multiple engineering elements, one of:>* {inclusive, exclusiveStatic, exclusiveDynamic}	*<Interaction mode between levels, one of:>* {sync, async, replace}	*<Any additional constraints that apply to the mapping>*



Engineering-Oriented Design (EOD)

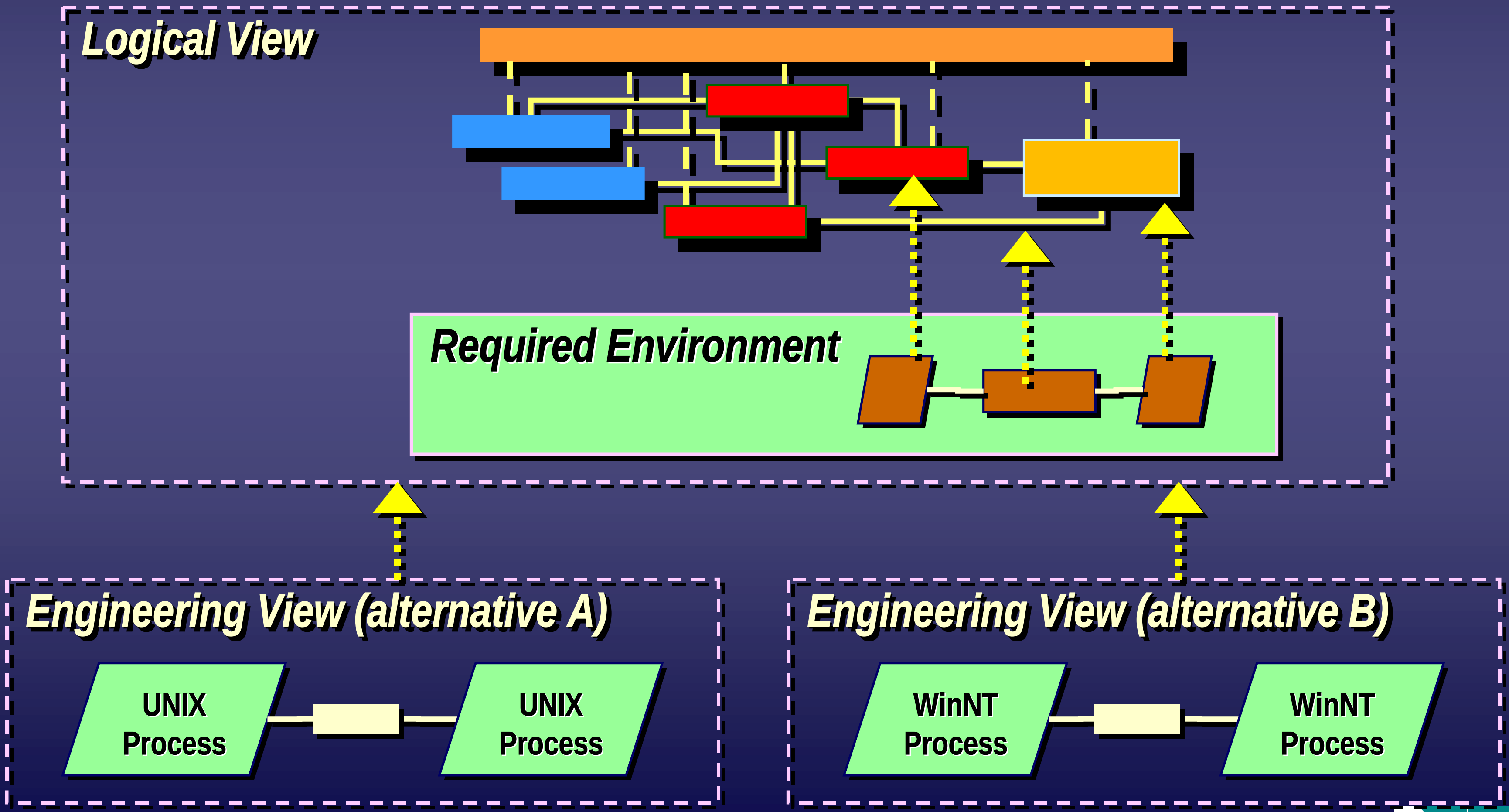
- *Analysis and design of software systems based on use of*
  - *Models*
  - *QoS specifications (accounting for physical properties)*
  - *Quantitative analysis techniques and simulation*
- Complements any model-based development method
- Advantages:
  - Higher reliability (simplification due to modeling)
  - Ability to predict system characteristics (and major design flaws) prior to full realization
  - Portability!

Achieving Portability with EOD

- Dilemma: *How can we account for the engineering aspects of the system without prematurely and possibly unnecessarily committing to a particular technology?*
- Approach: *Provide an abstract technology-independent but quantified specification of the required characteristics of the engineering model as part of the logical model*

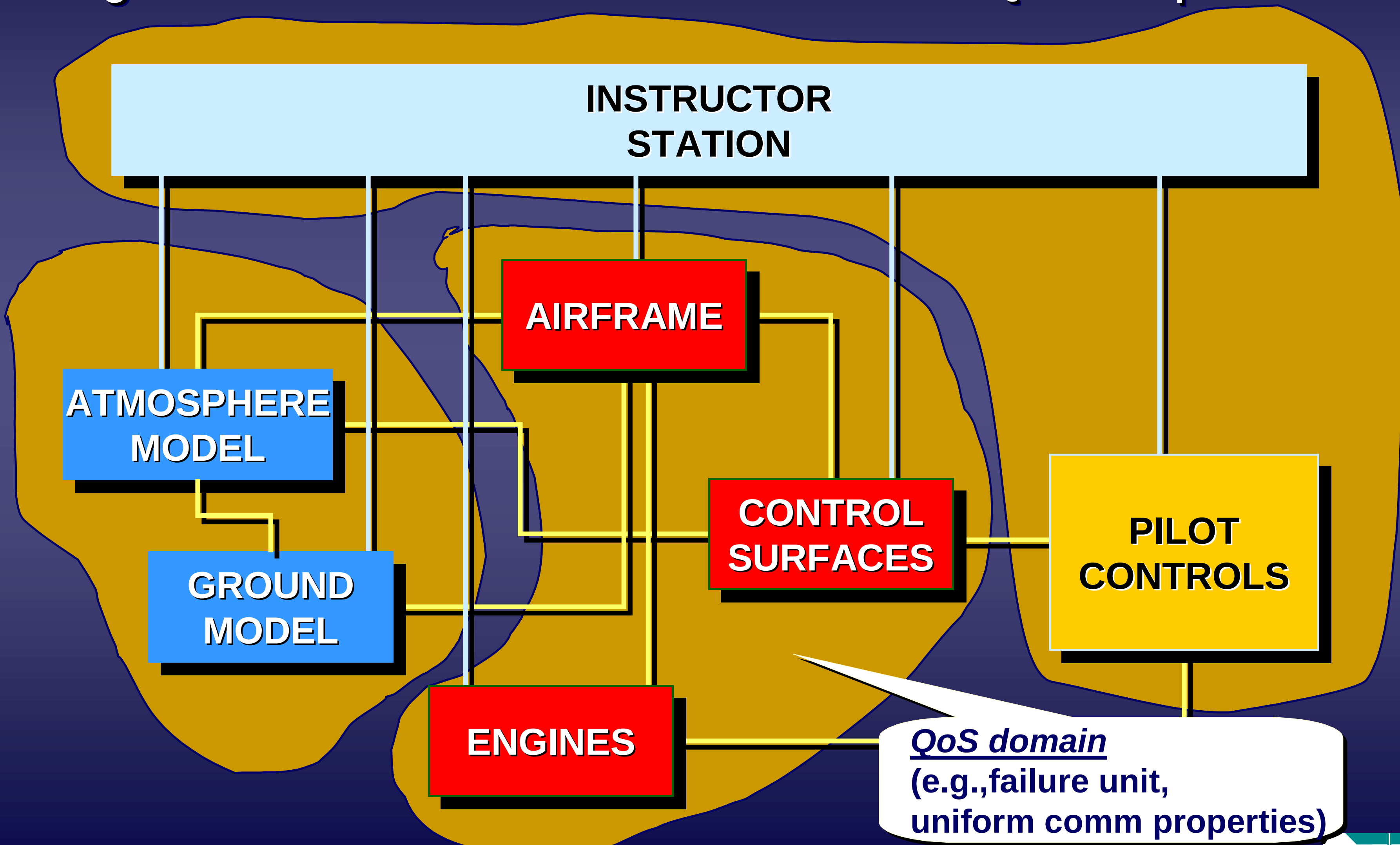
Viewpoint Separation

- *Required Environment:* a technology-neutral environment specification required by the logical elements of a model



Required Environment Partitions

- Logical elements often share common QoS requirements

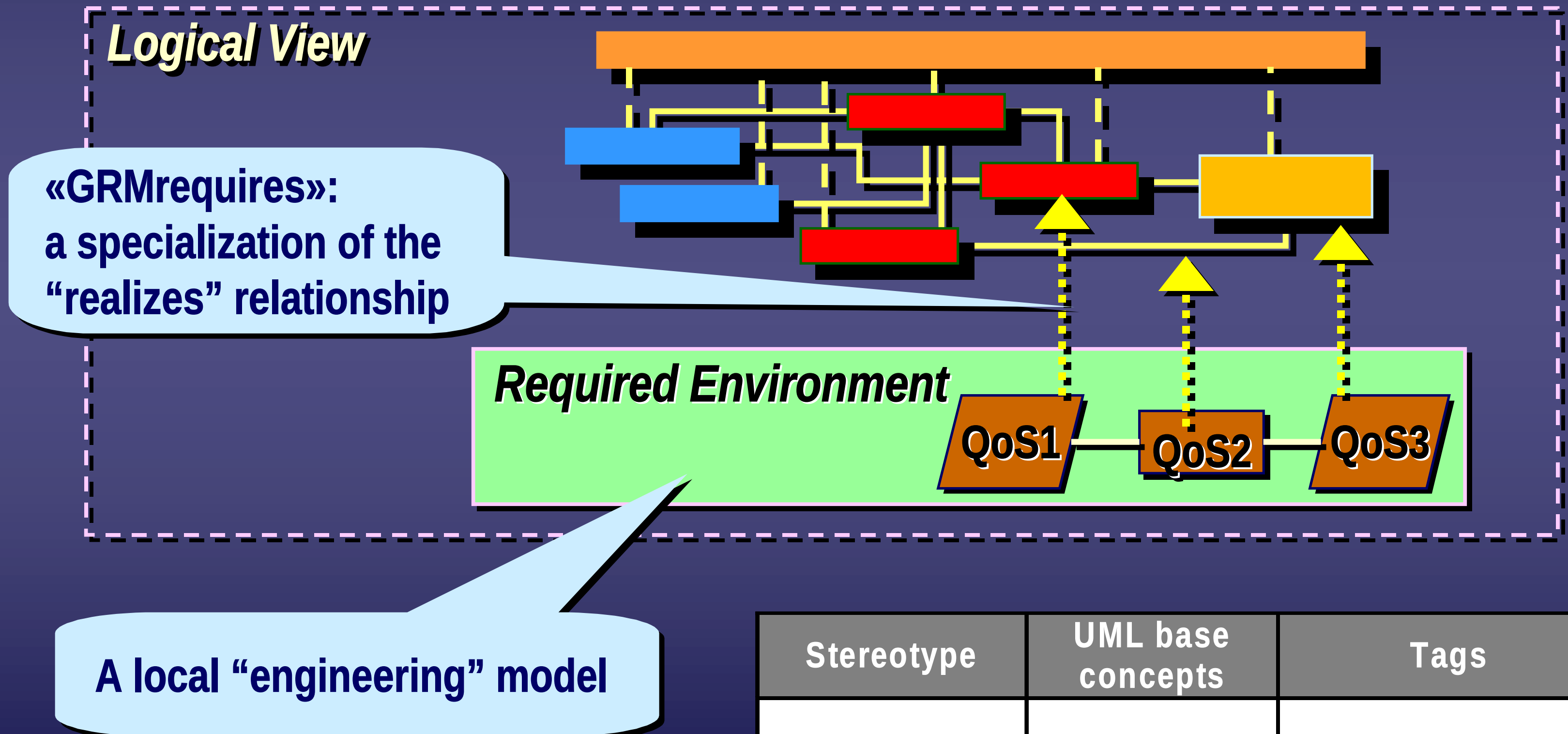


QoS Domains

- Specify a domain in which certain QoS values apply universally:
  - failure characteristics (failure modes, availability, reliability)
  - CPU performance
  - communications characteristics (delay, throughput, capacity)
  - etc.
- The QoS values of a domain can be compared against those of a concrete engineering environment to see if a given environment is adequate for a specific model

Modeling QoS Domains in UML

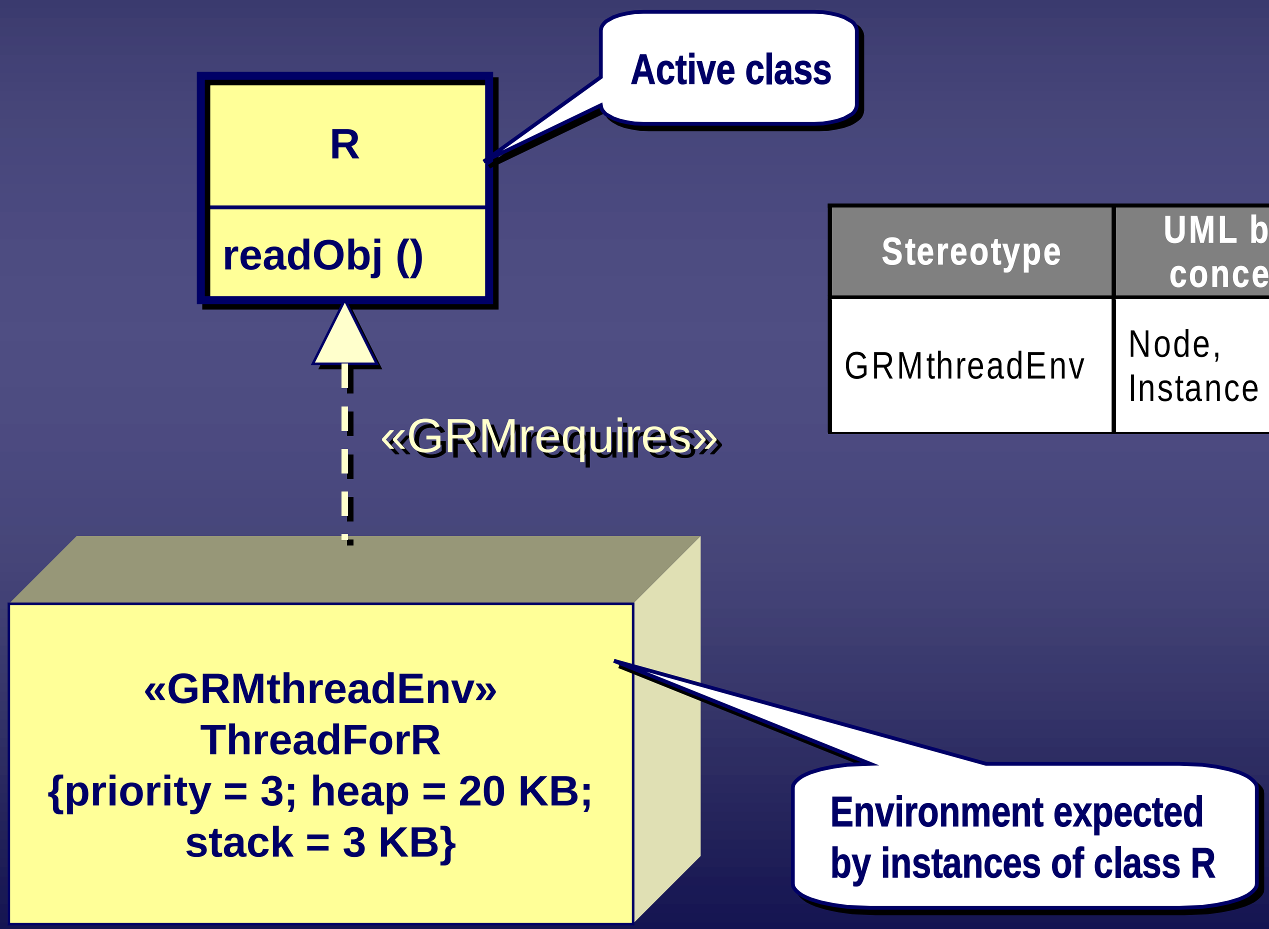
- Similar to realization: mapping of logical elements to a desired (required) engineering environment



Stereotype	UML base concepts	Tags
GRMrequires	GRMrealizes	N/A

Example: QoS Domain for an Active Object

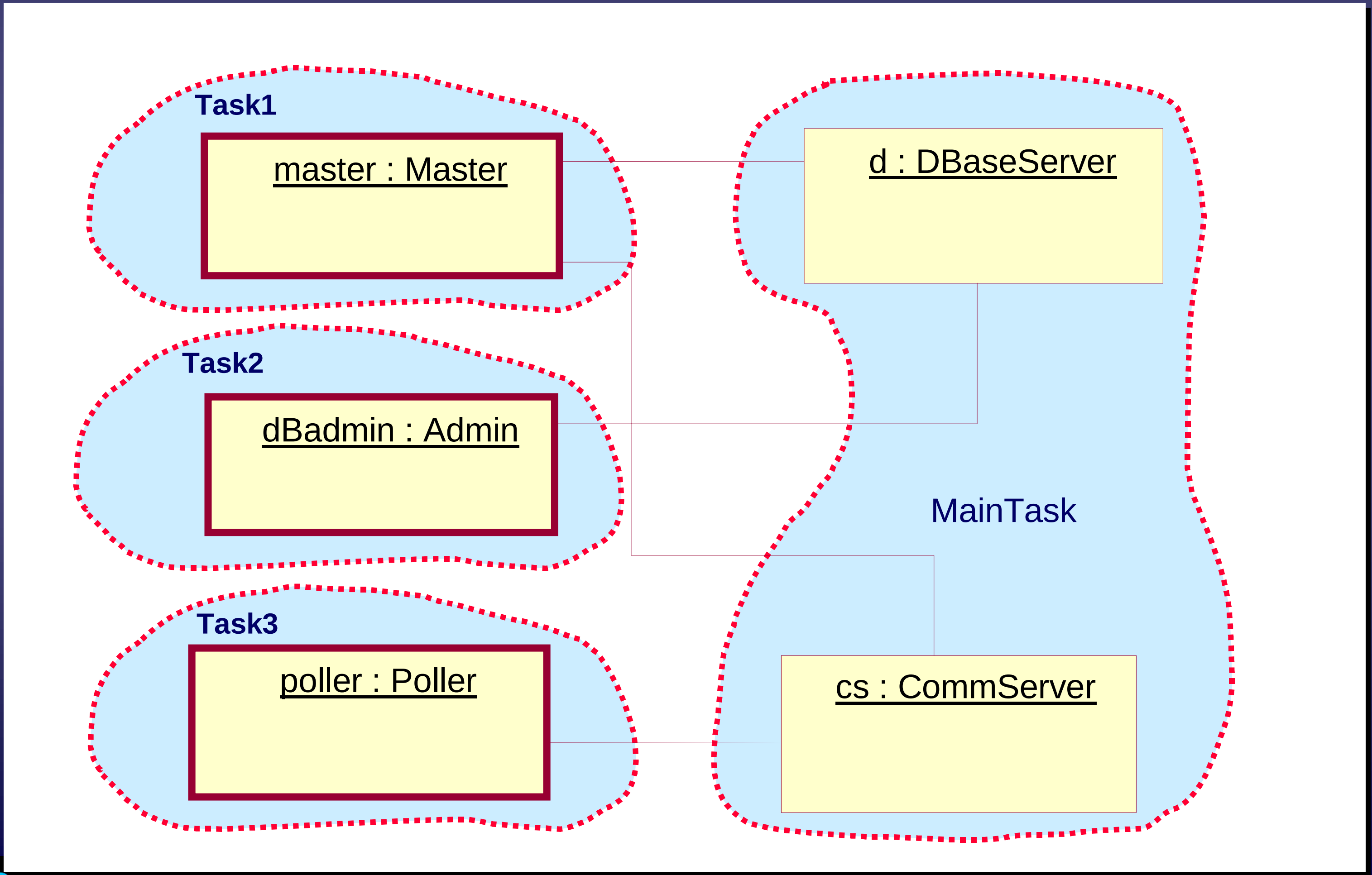
- Using a stereotype of Node
  - in conjunction with the “required environment” relationship



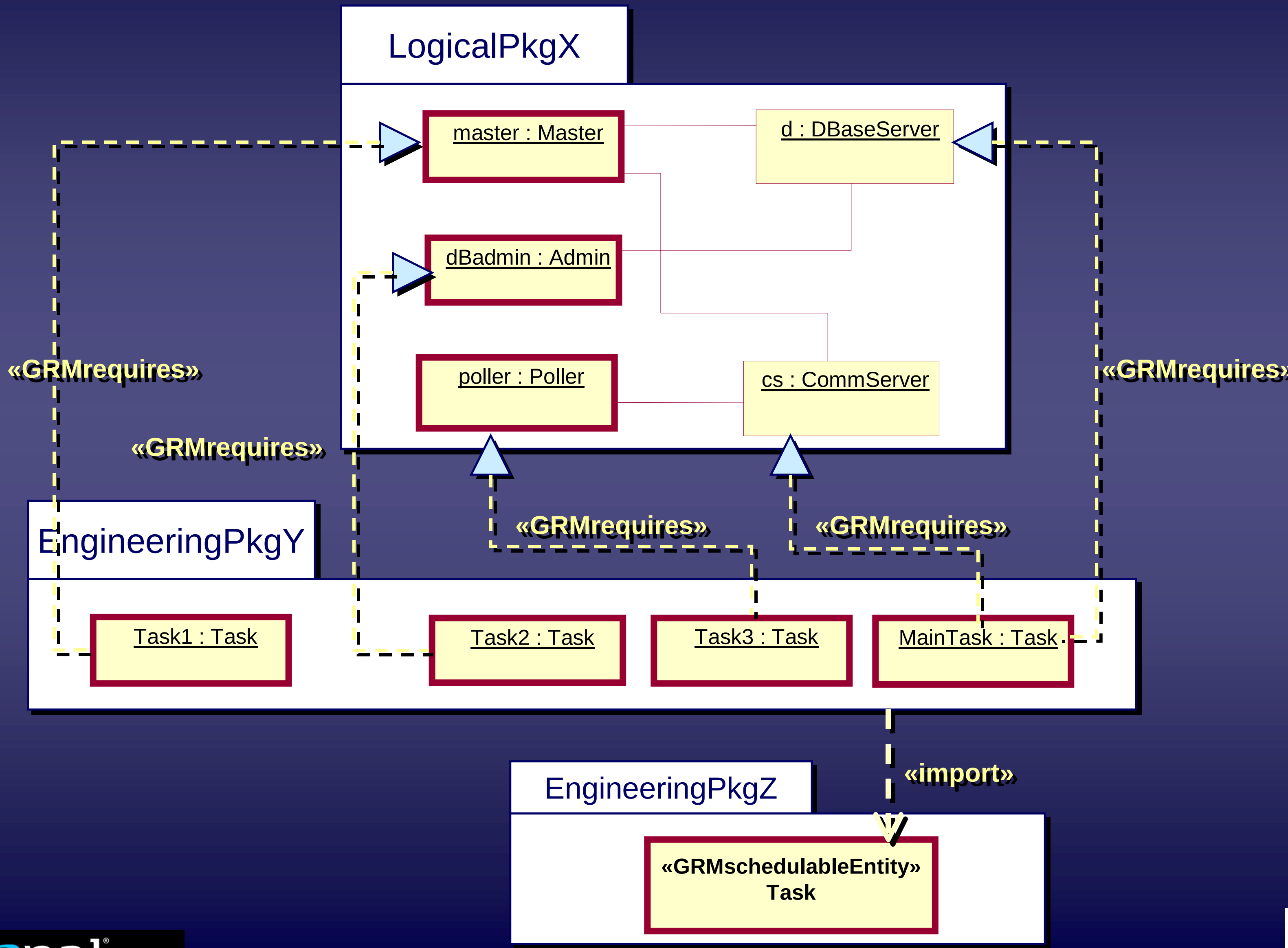
Stereotype	UML base concepts	Tags
GRMthreadEnv	Node, Instance	priority [0..1] : Integer heap [0..1] : Real stack [0..1] : Real

Example: Task Allocation

- The allocation of logical model to engineering model elements

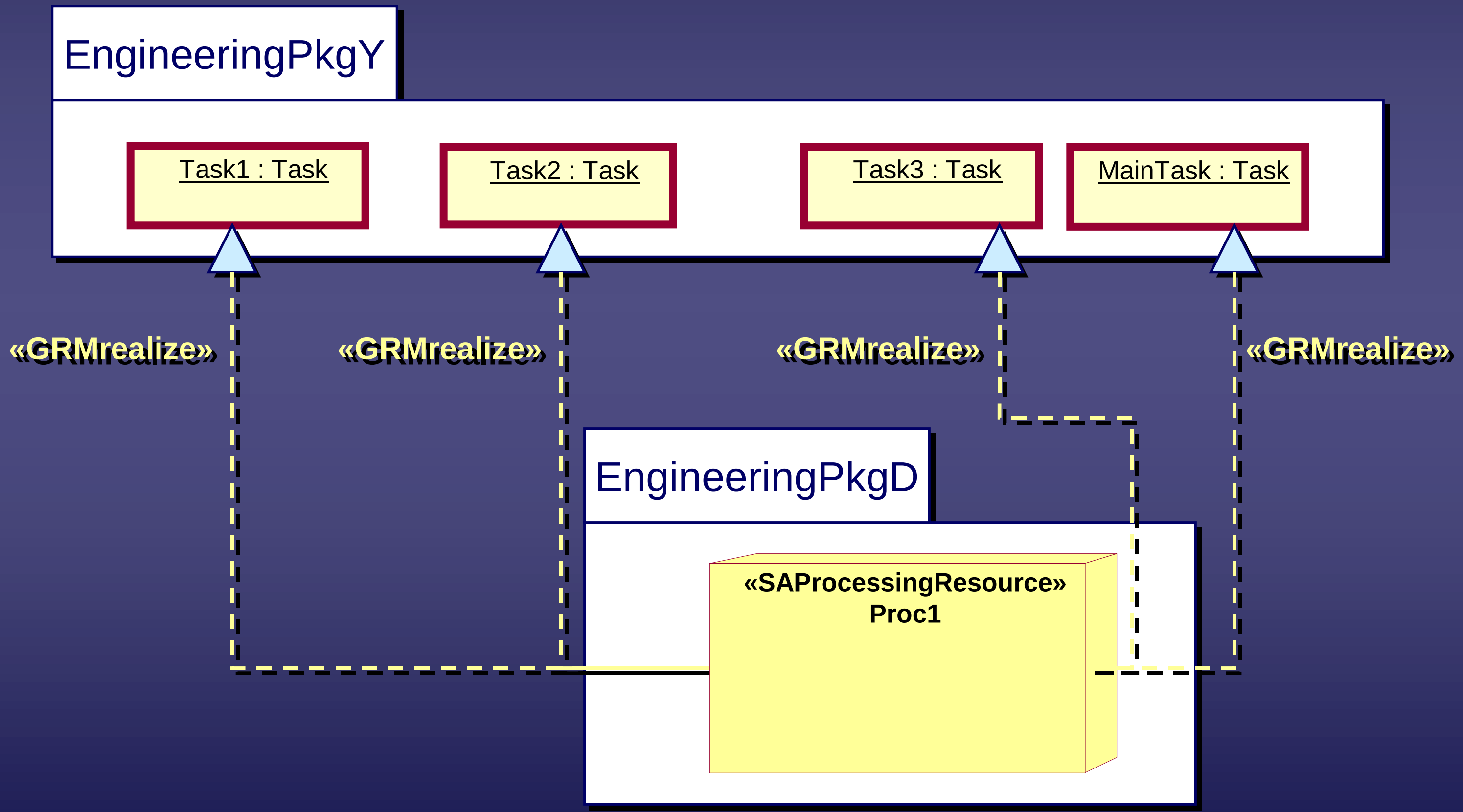


Example: UML Model of Allocation



Example: Completing the Mapping

- Mapping to hardware



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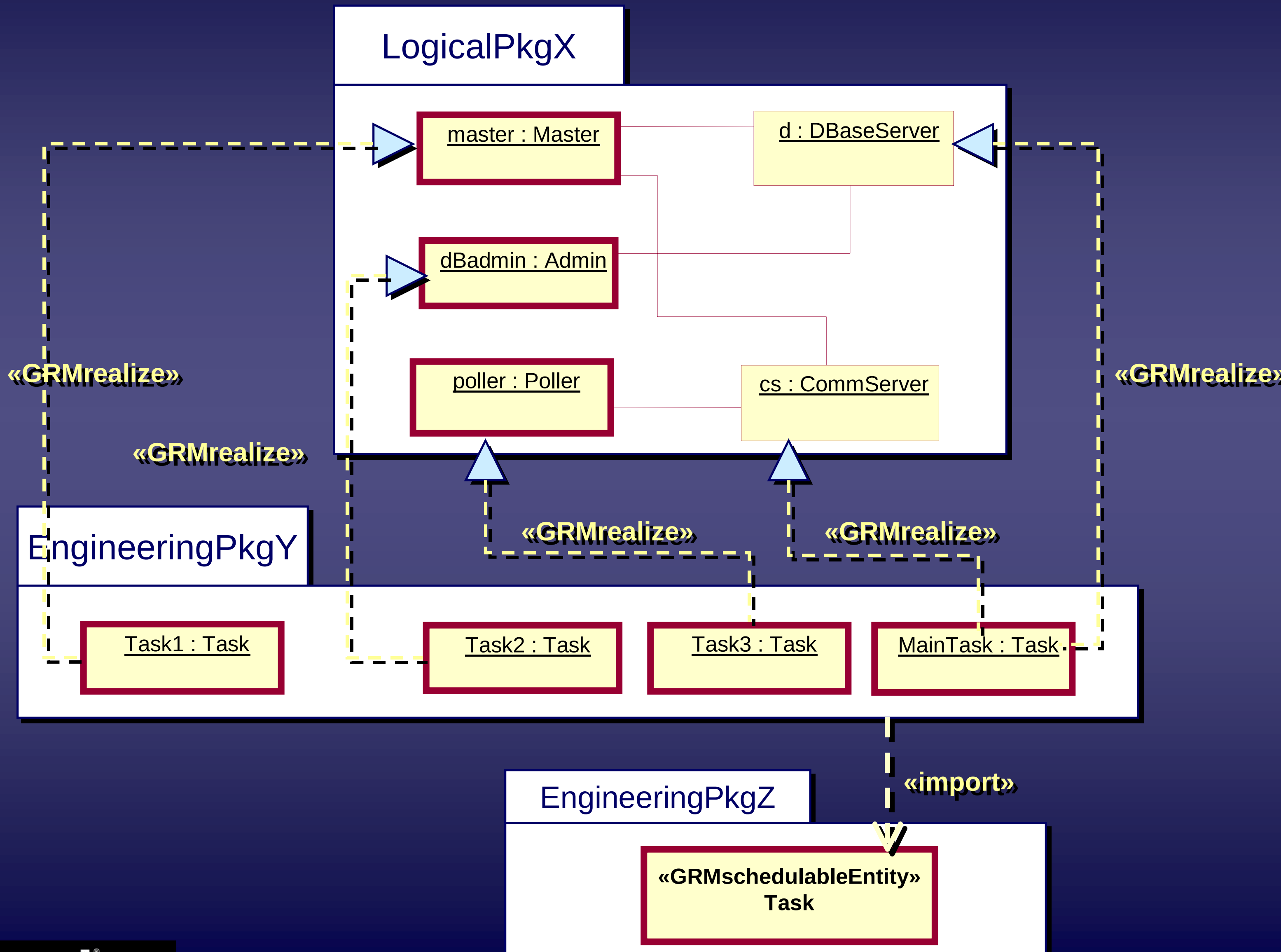

Example: Completing the Mapping

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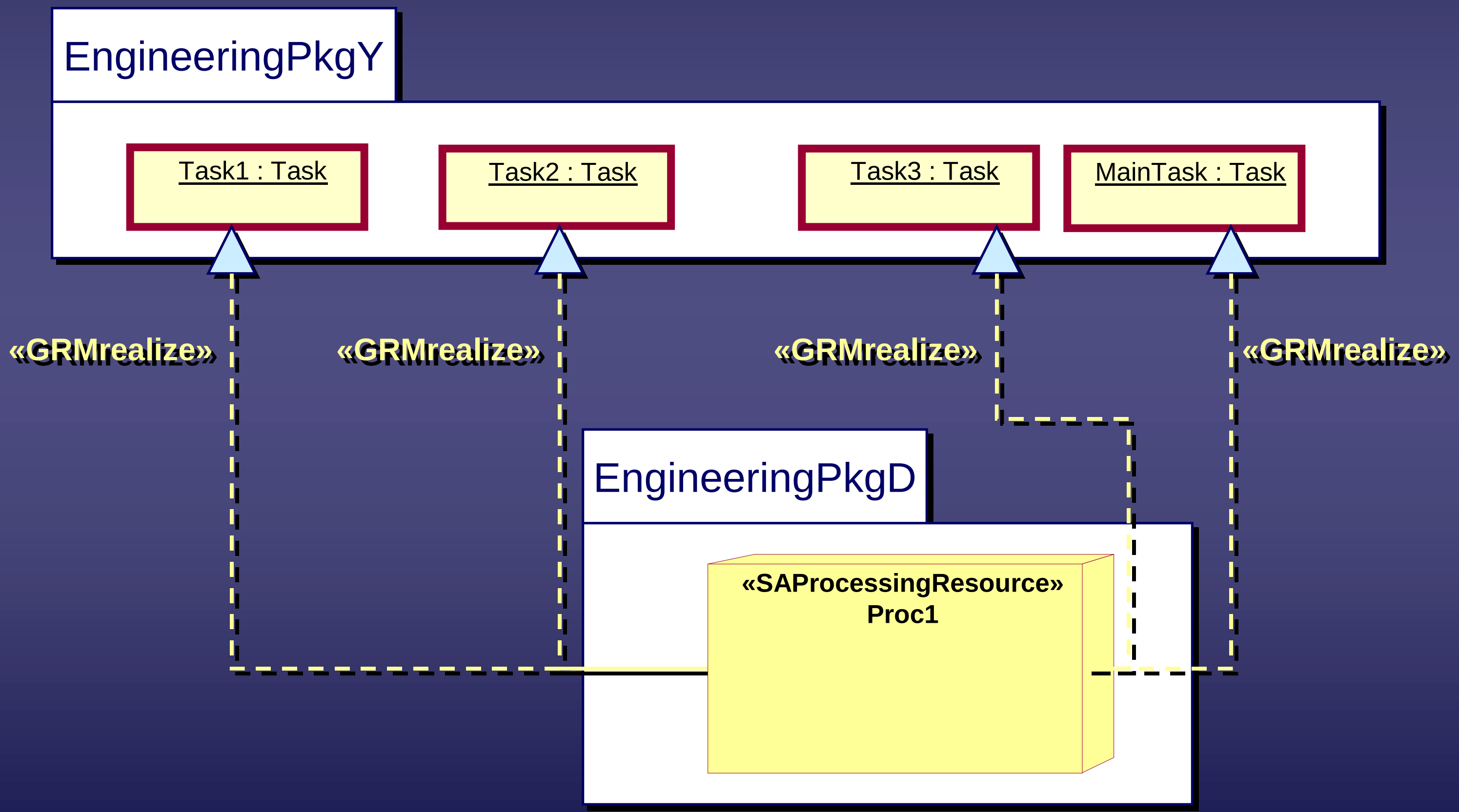

Summary: RT Design and Engineering

- In complex RT systems, the logical design is strongly influenced by the characteristics of the engineering environment
- In such systems, it is often crucial to formally determine if a system will meet its non-functional requirements (throughput, response time, availability, etc.)
- The QoS-based approach described here can serve as a basis for:
  - quantitative analysis of UML-based models
  - a real-time modeling standard that will facilitate automated exchange between design and analysis tools

- Real-Time Systems and the Object Paradigm
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Summary: The Problem

- Complexity!
- The design of real-time systems is influenced significantly by the physical properties of:
  - the environment in which the system exists
  - the implementation technology
- Most of them stem from the physical world
  - the physical dimension plays a major role in the design of real-time software since it imposes limitations on the logical design

Summary: The Solution (1 of 2)

- *The object paradigm*
  - reduces incidental complexity
  - its structural bias is better suited to the real-time domain than the procedural paradigm
  - additional key features (encapsulation, inheritance, polymorphism, etc.) add further expressive power
- *Engineering-oriented design*
  - accounts for the physical dimension during logical design
  - based on a quality of service (QoS) framework as represented in the generic resource model
  - allows de-coupling from actual implementation technologies (through required environment specifications)
  - suitable for analysis and synthesis
  - enables early detection of critical design flaws

Summary: The Solution (2 of 2)

- UML provides a common and standardized underpinning that supports all the components of our solution
  - for object-oriented modeling
  - for predictive QoS modeling (via the real-time profile)
  - for design analysis and synthesis (tool interchange)
  - for architectural definition
  - for implementation (through full automatic code generation)
- Furthermore, as a standard, it enables model interchange between specialized tools and is a basis for significant automation of the RT software development process

Where to Obtain the RT Profile

A copy of the real-time standard submission can be obtained from the Object Management Group website at:

http://www.omg.org/cgi-bin/doc?ad/2001-06-14

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