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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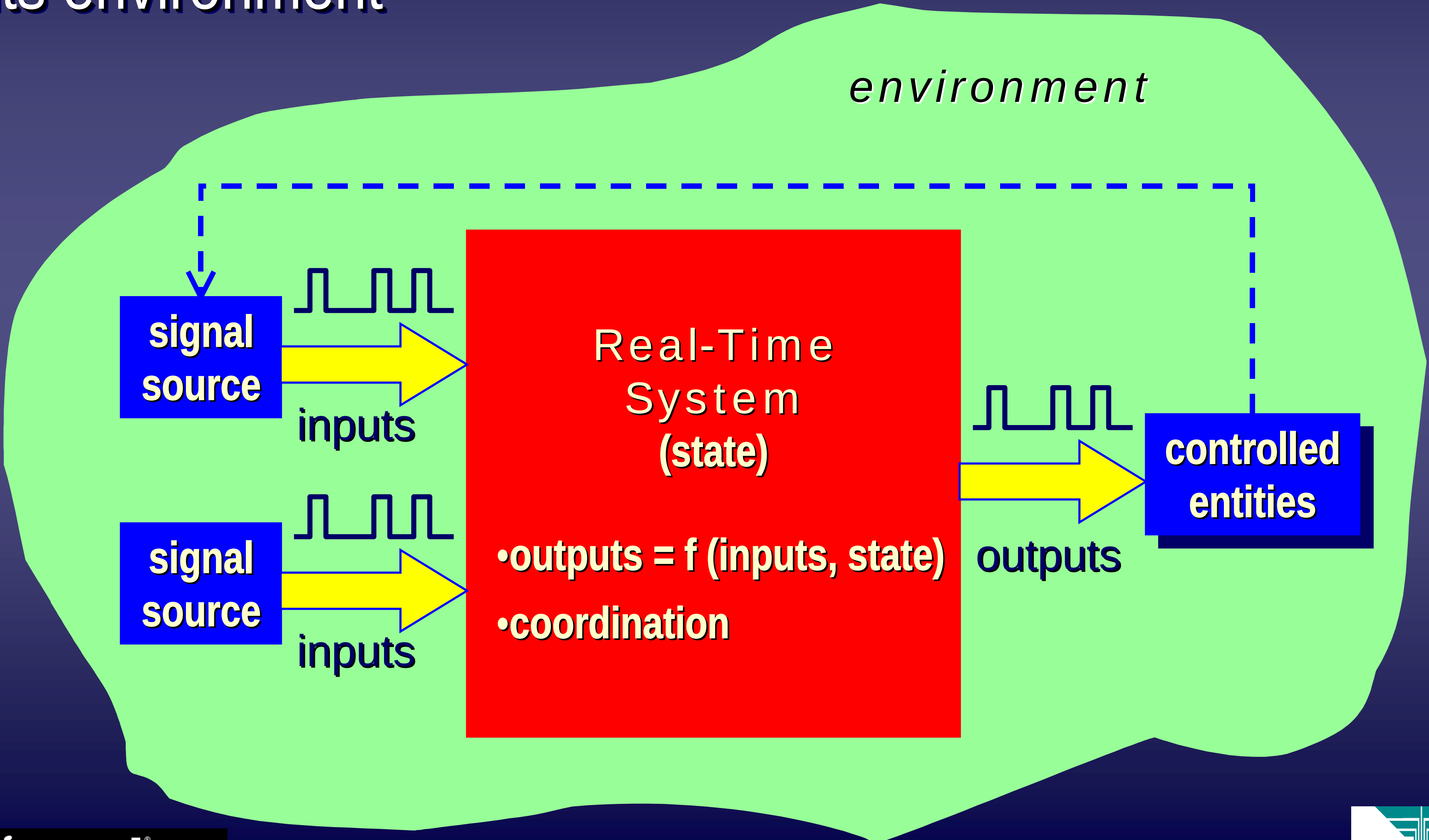
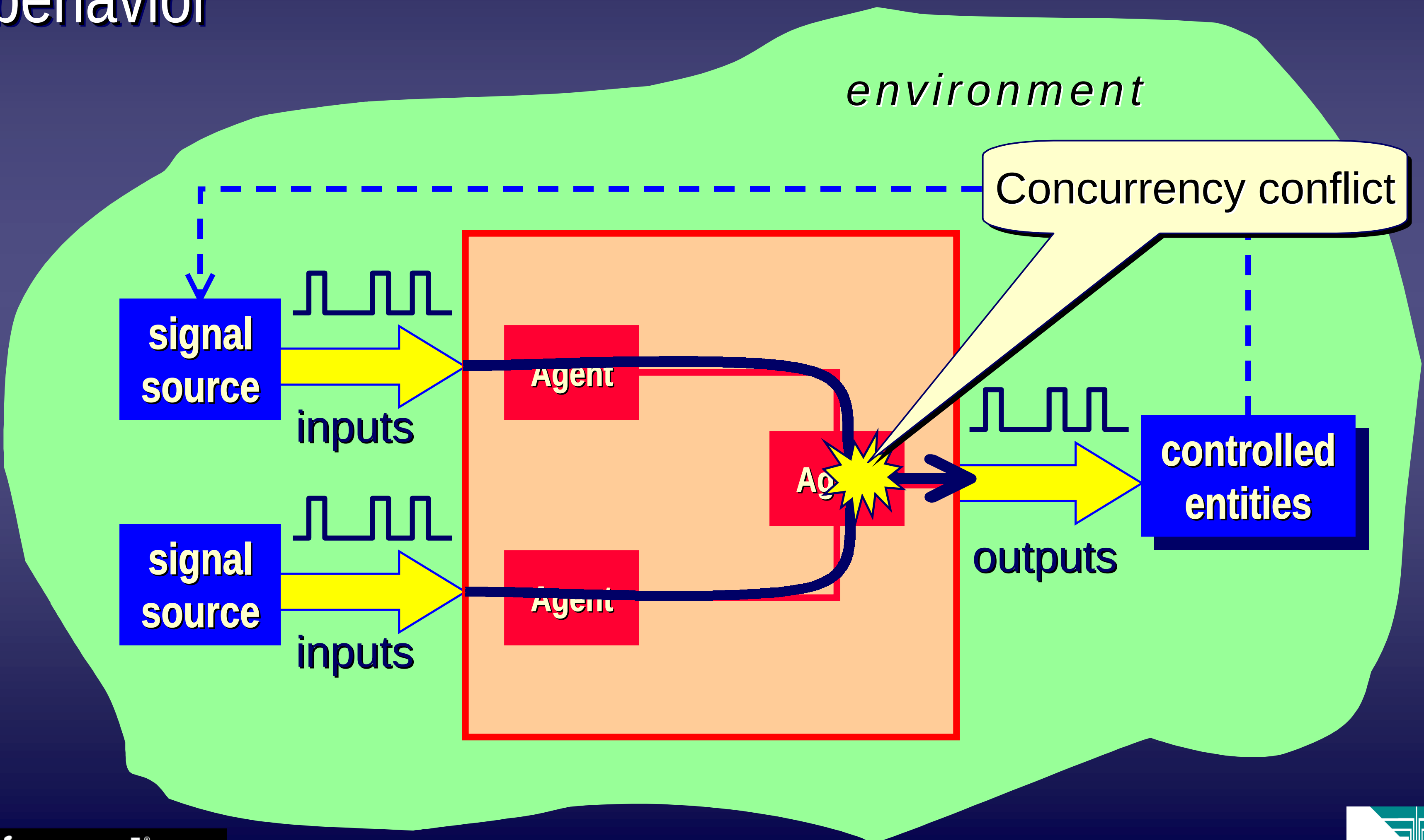
Real-Time System

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



Under the Hood

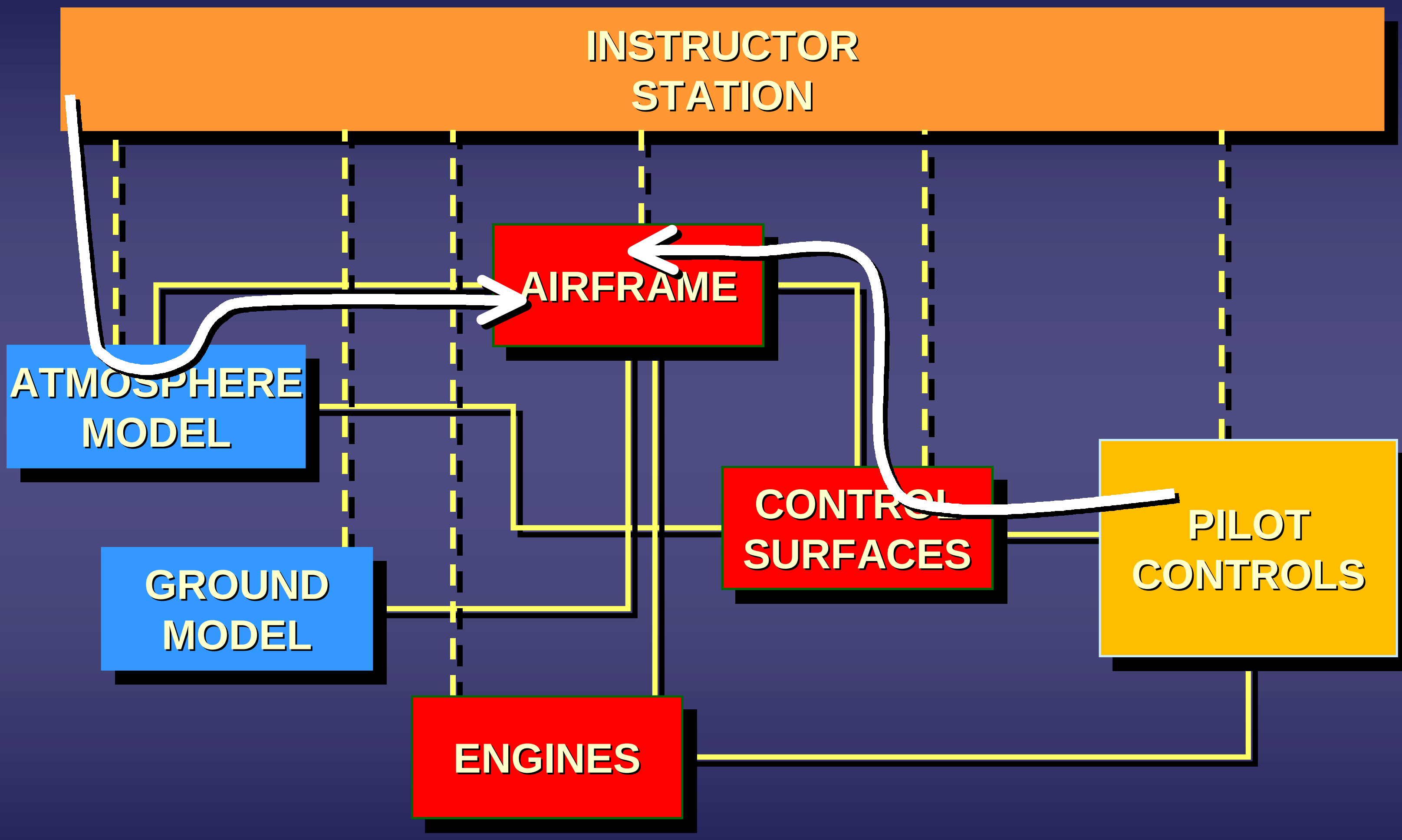
- A persistent structure that provides a framework for behavior



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

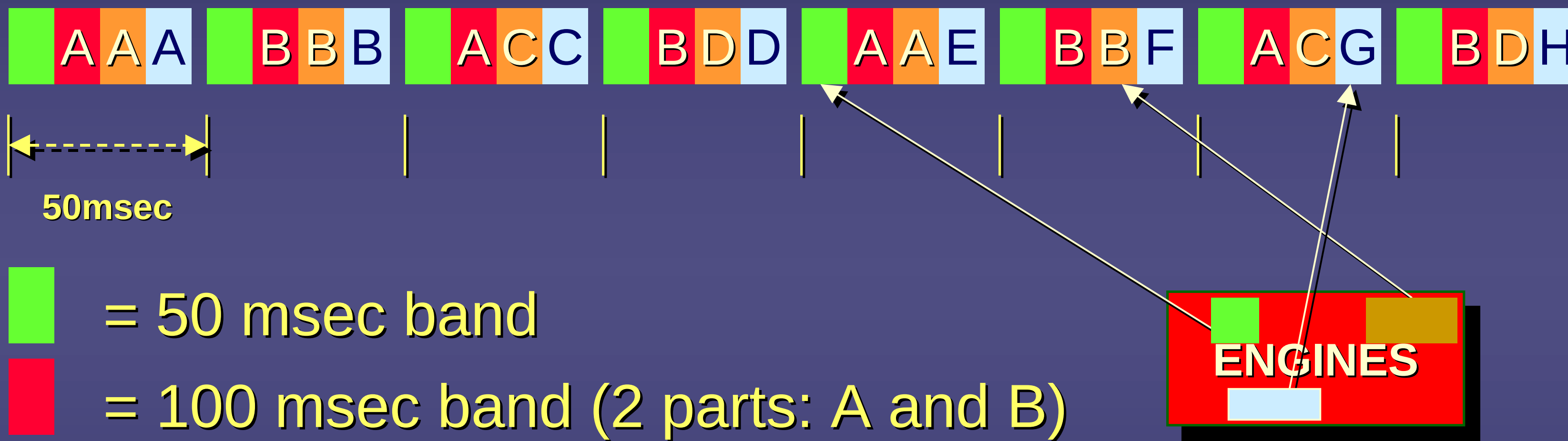
Sample Real-Time Application



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

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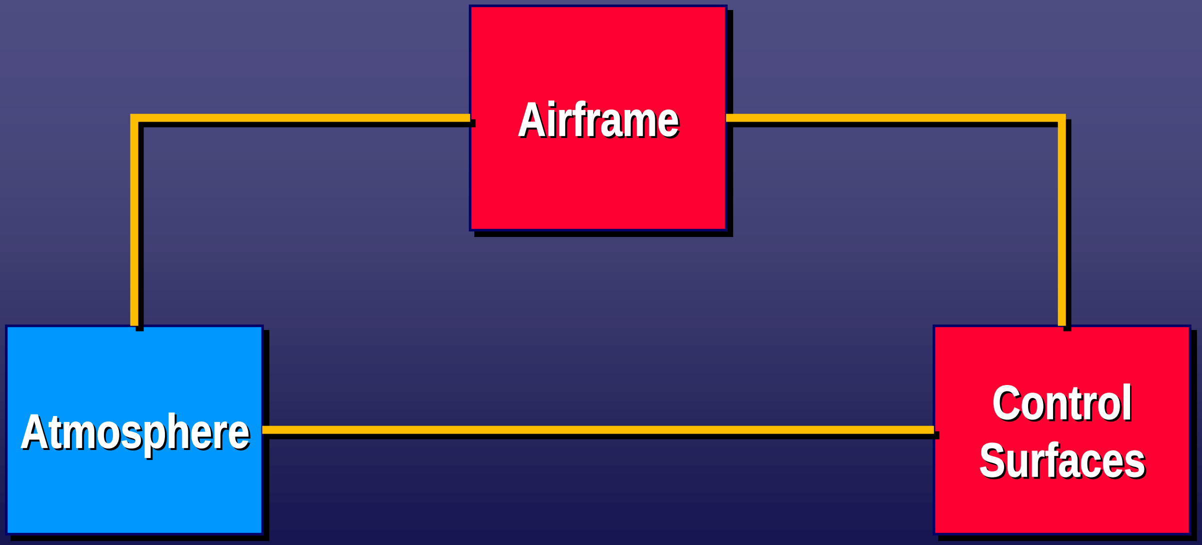
The Essence of the Object Paradigm

- 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...

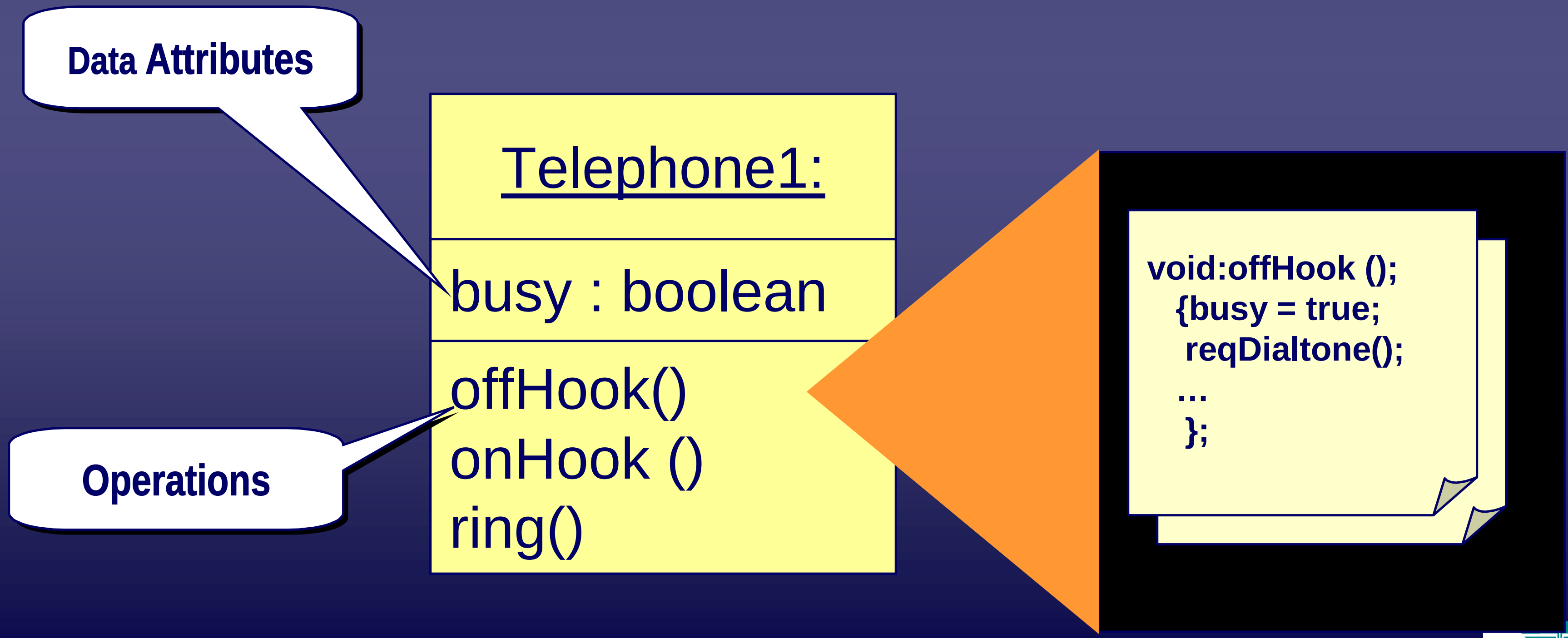
- Performance?
  - the cost of abstraction (encapsulation, automatic garbage collection, dynamic binding, etc.)
- Modeling real-time specific phenomena?
  - time and timing mechanisms
  - resources (processors, networks, semaphores, etc.)
- Exploiting current real-time system theory?
  - schedulability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

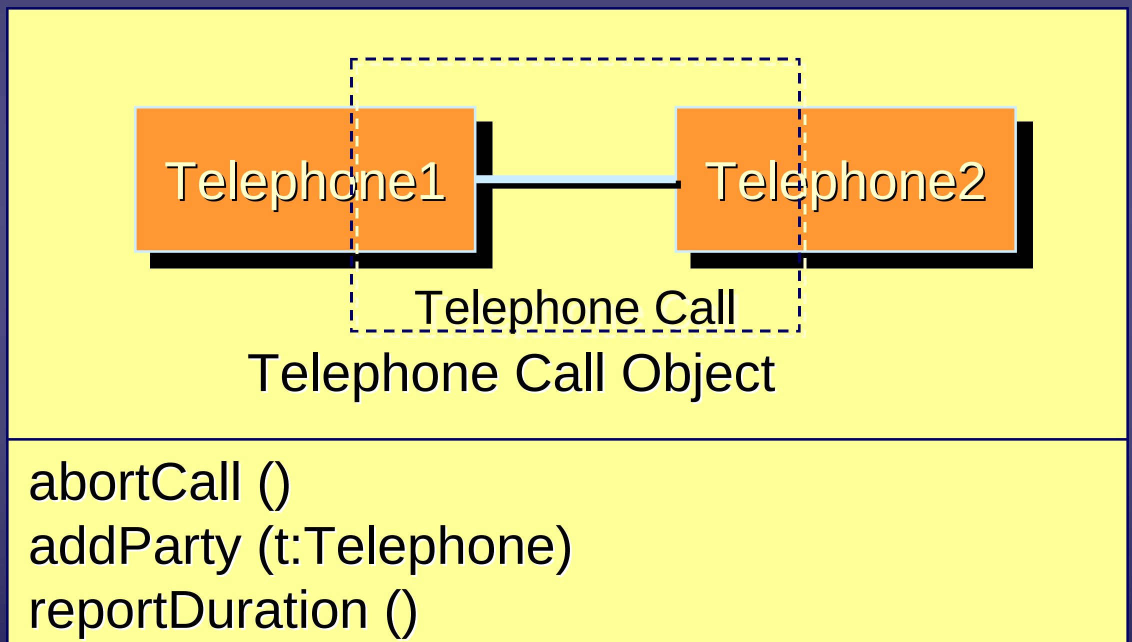
Objects

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



Conceptual Objects

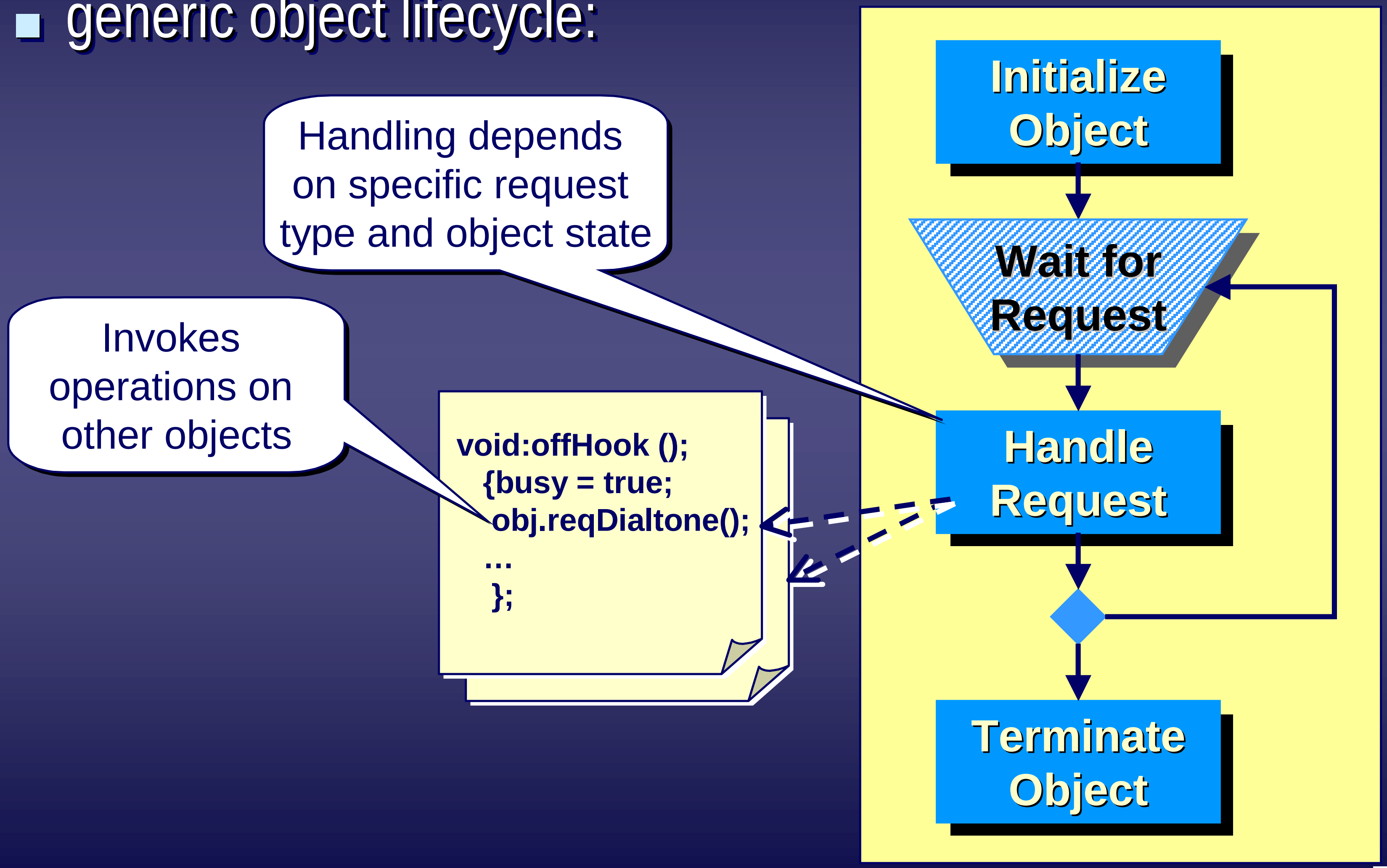
- Not all objects necessarily require a physical underpinning
- For example, the “telephone call” object



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

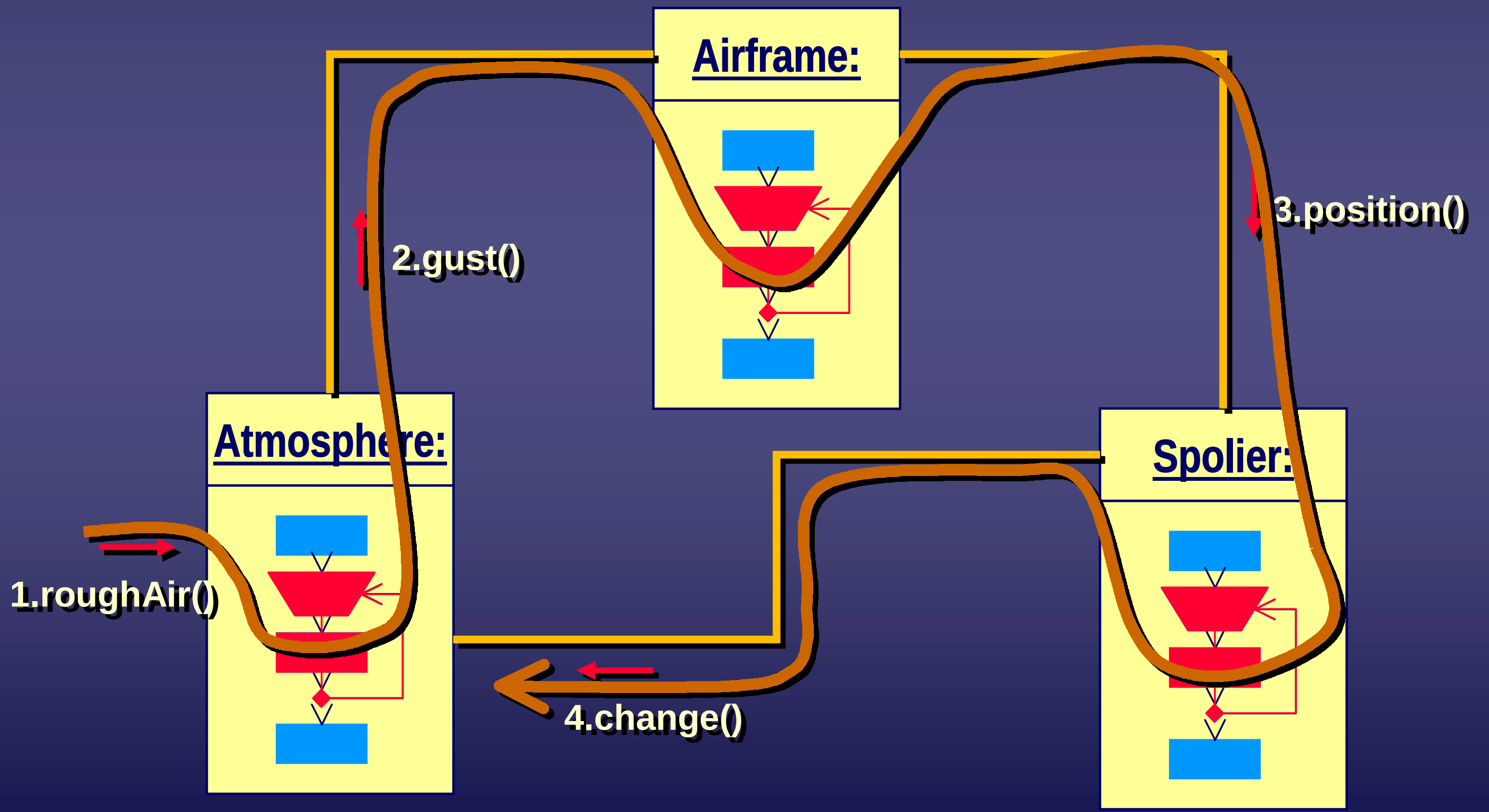
Object Behavior

- 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

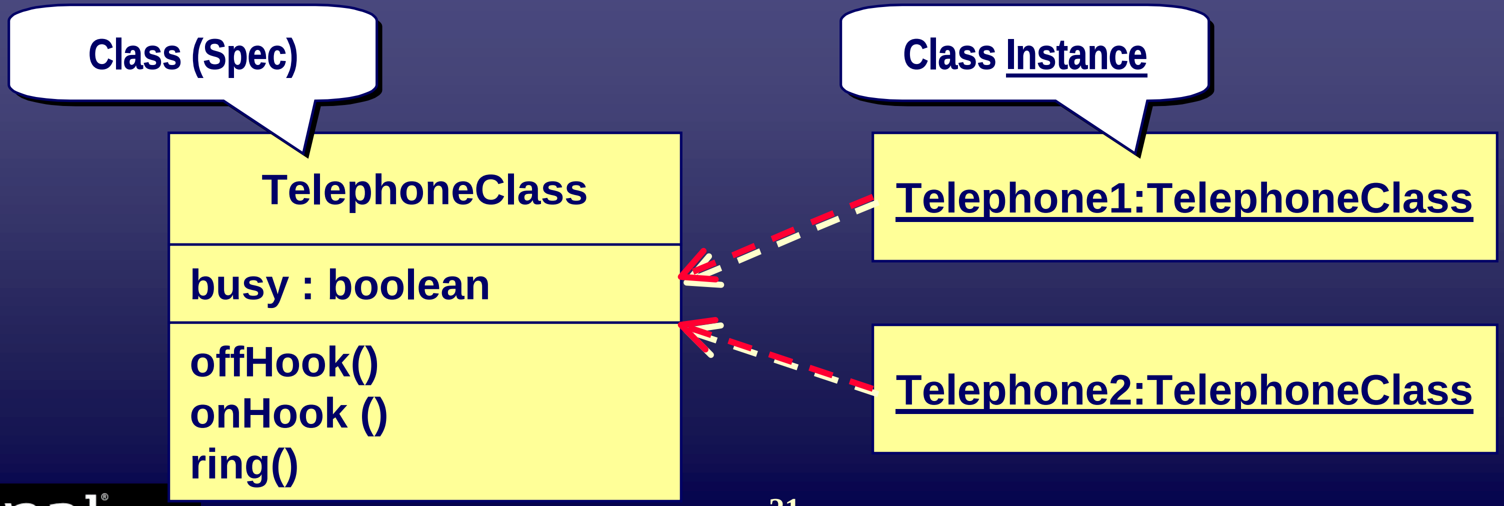


Objects and Emergent Behavior

- 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

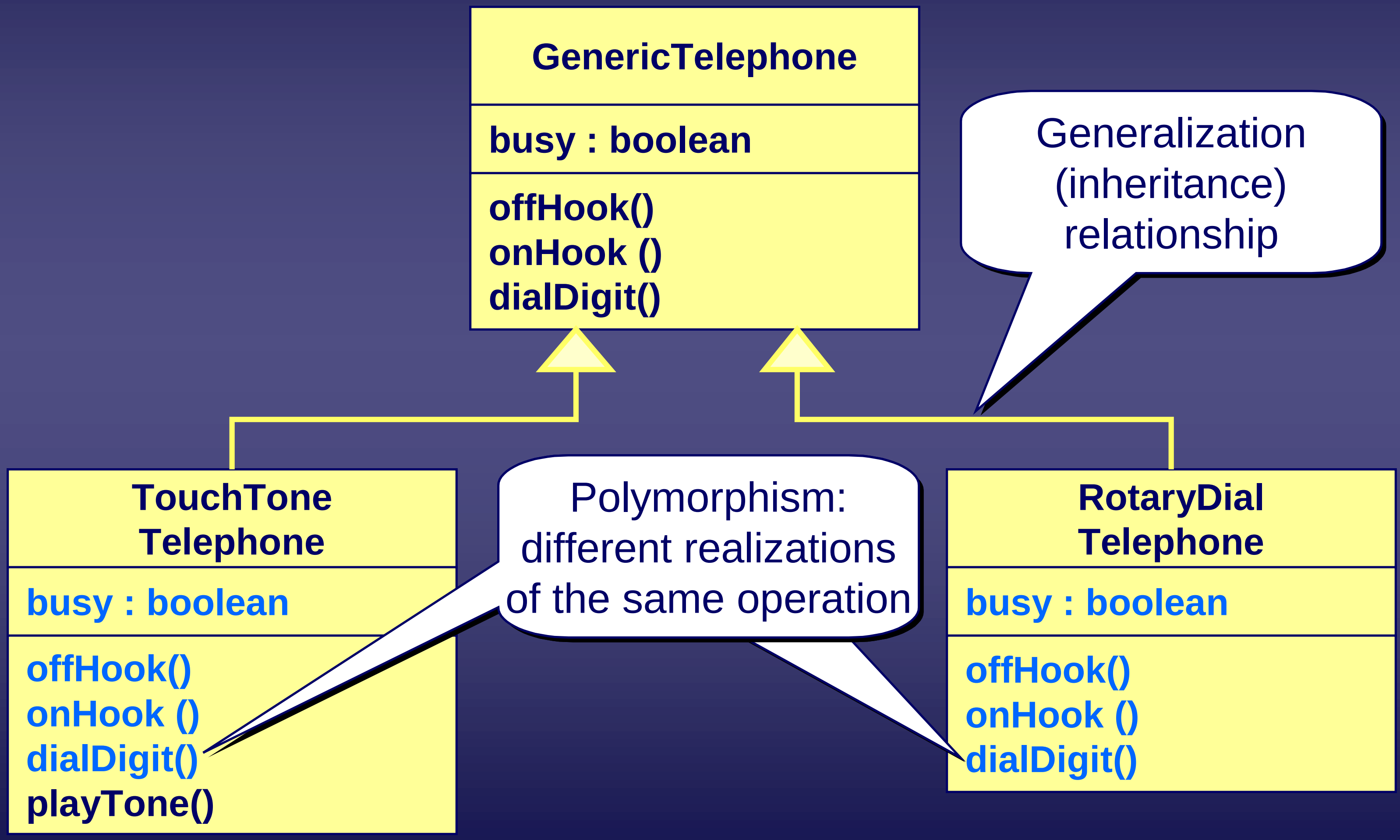
Classes and Instances

- 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

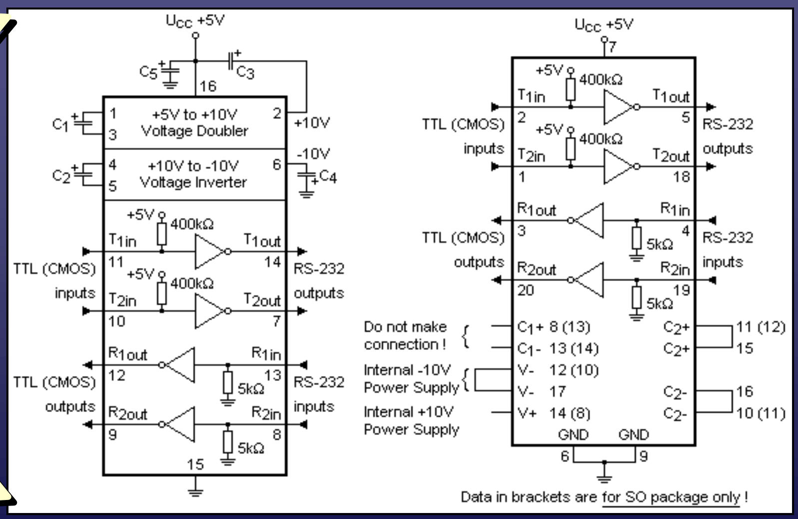
Components of UML

- 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 model of a system based on a particular viewpoint
  - abstracts out detail that is irrelevant for that set of concerns

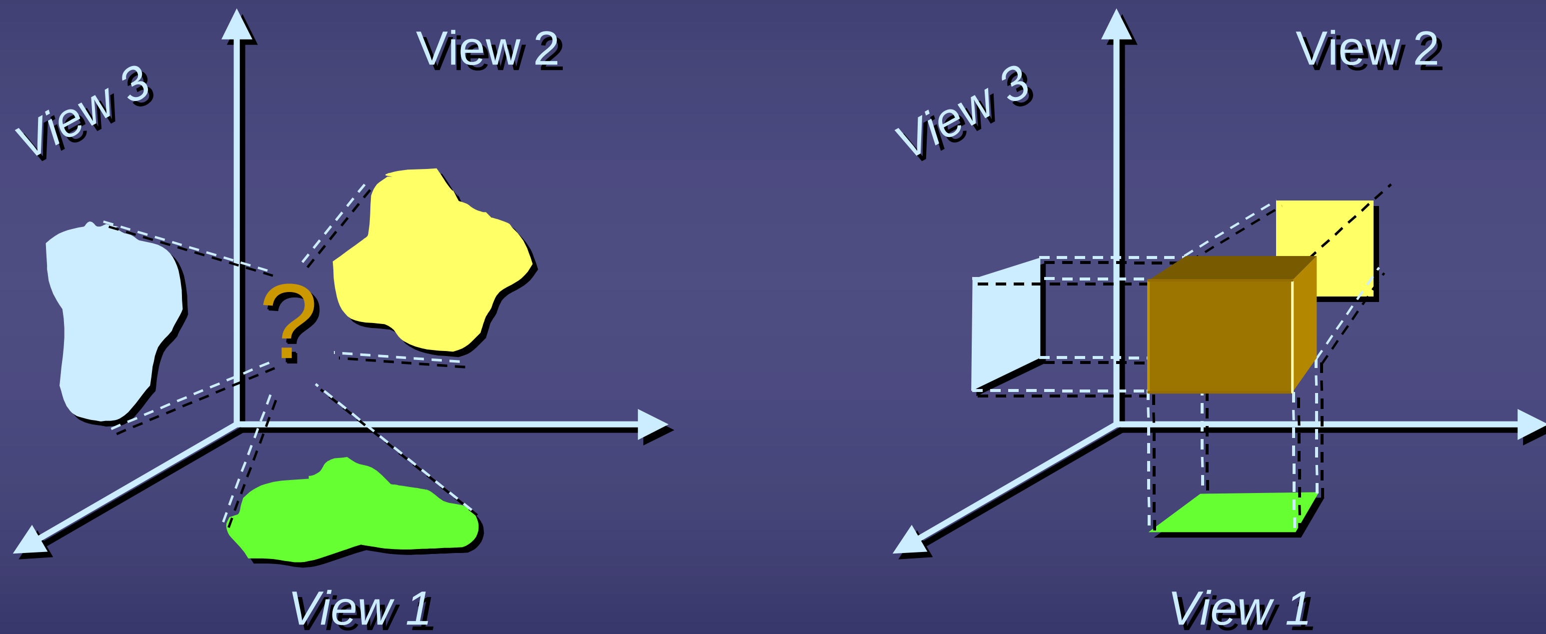
Radio: Designer view



Radio: Radio: user view

Model-Based and View-Based Approaches

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



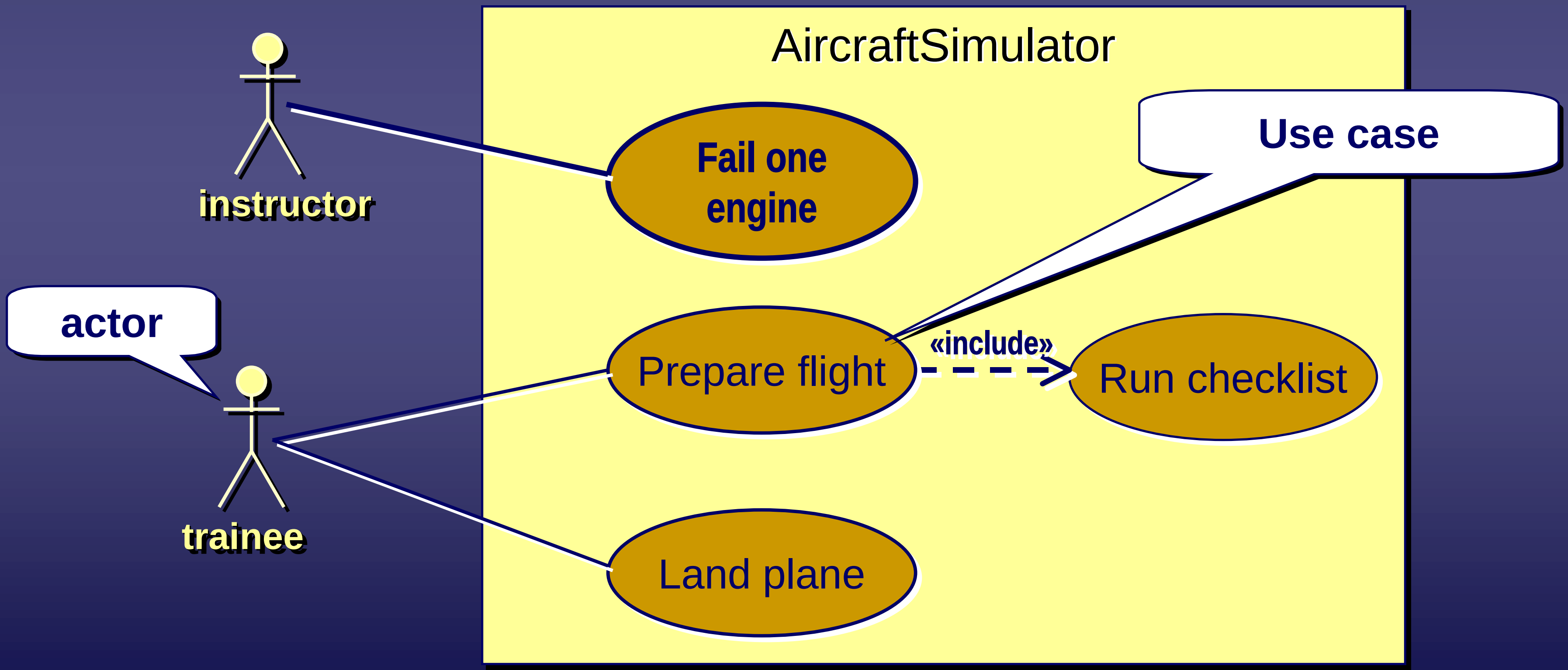
Model-view consistency is enforced through the UML metamodel

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

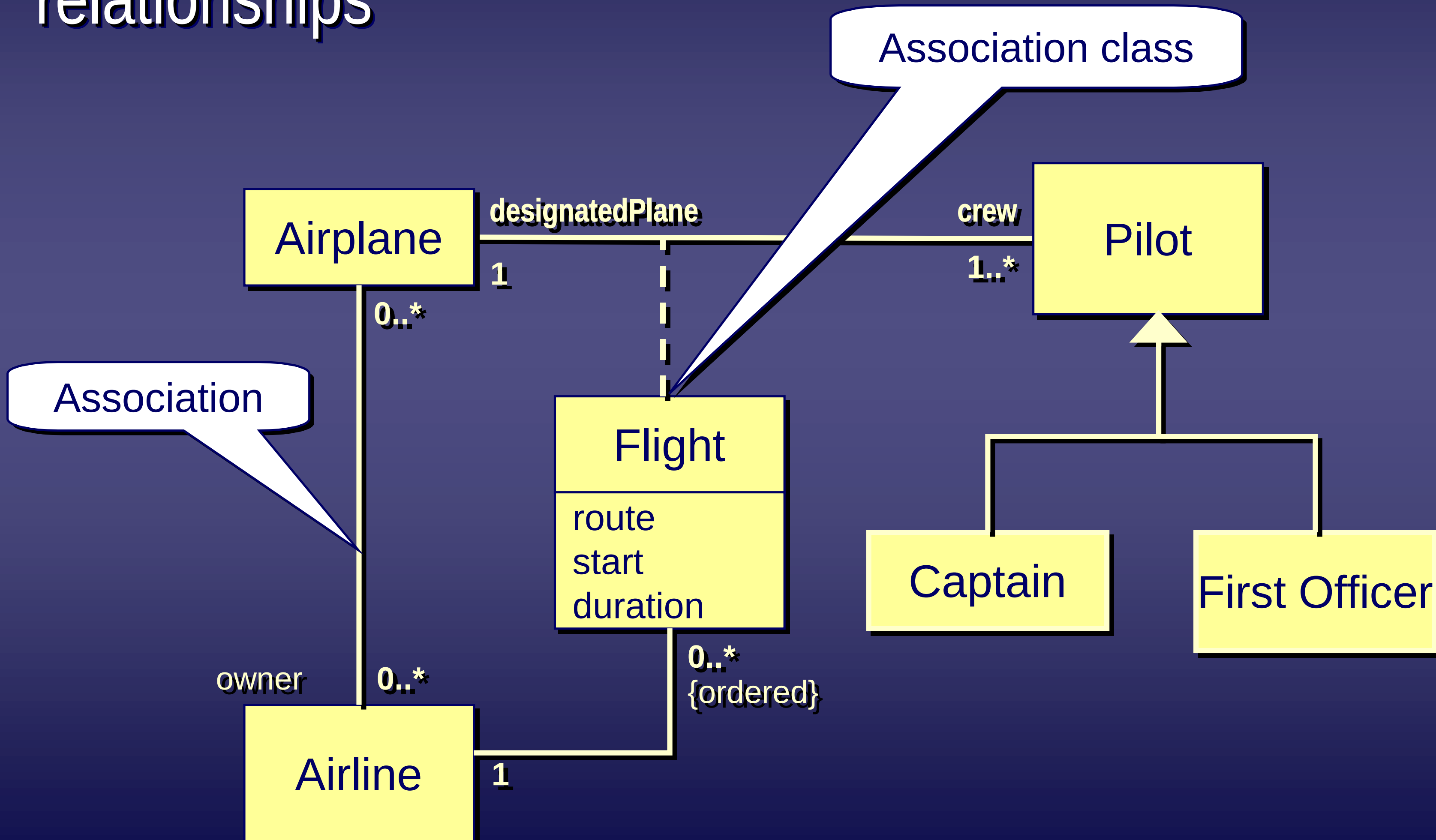


Use Cases and RT Systems

- 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

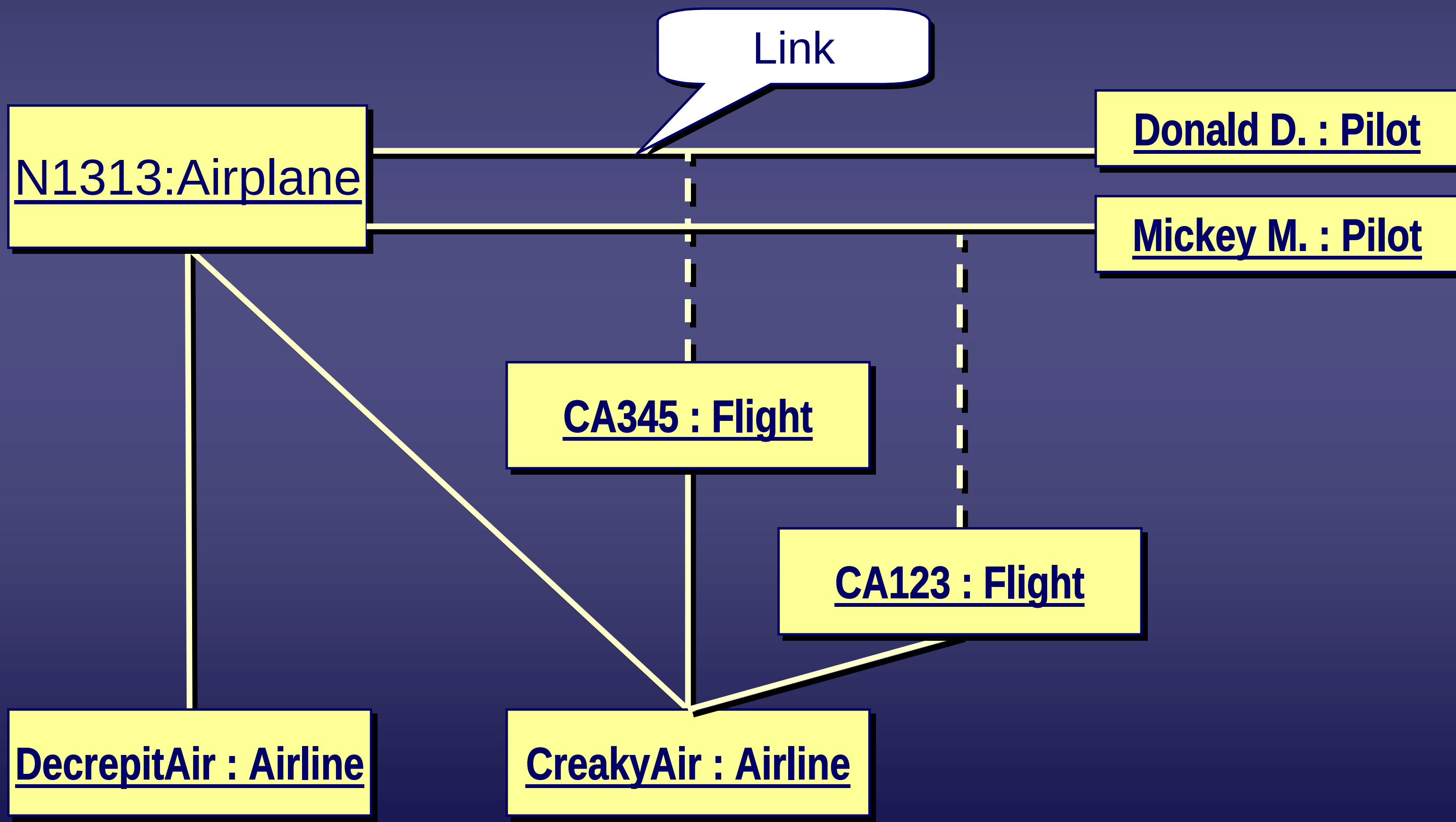
Class Diagram

- Shows the entities in a system and their general relationships



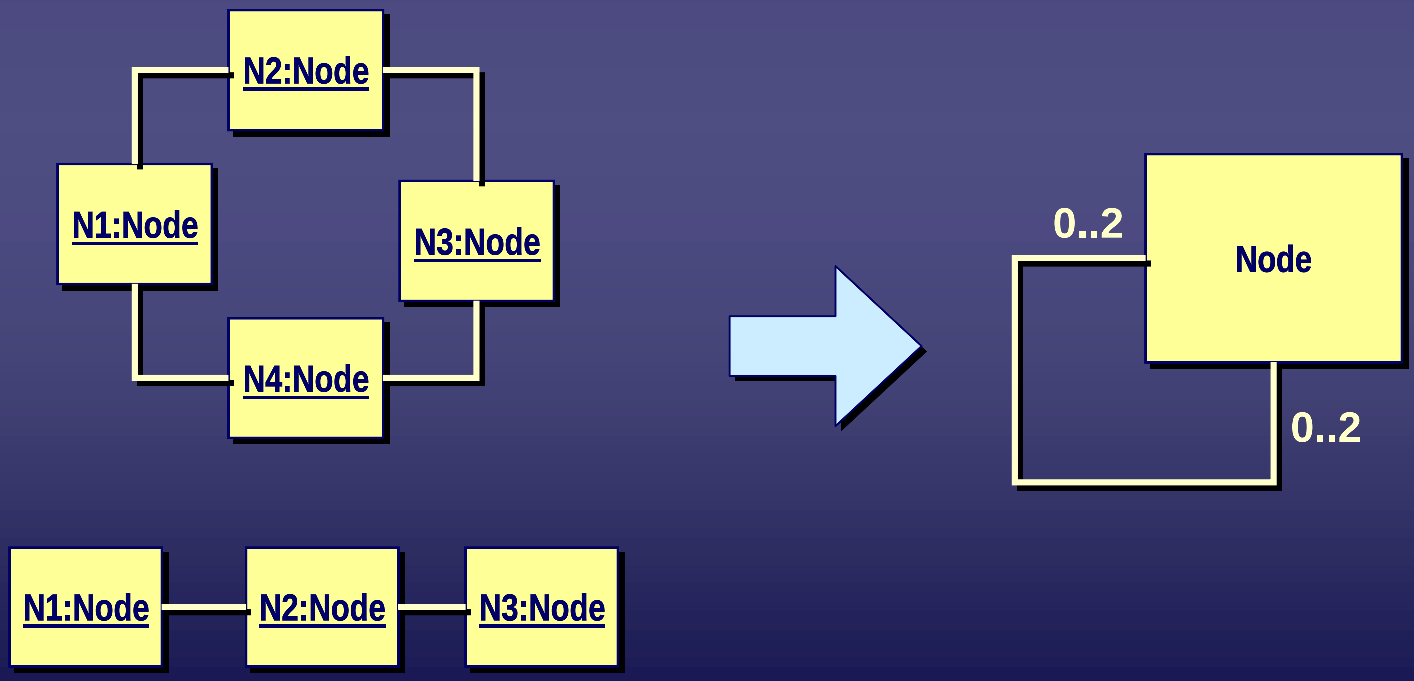
Object Instance Diagram

- 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

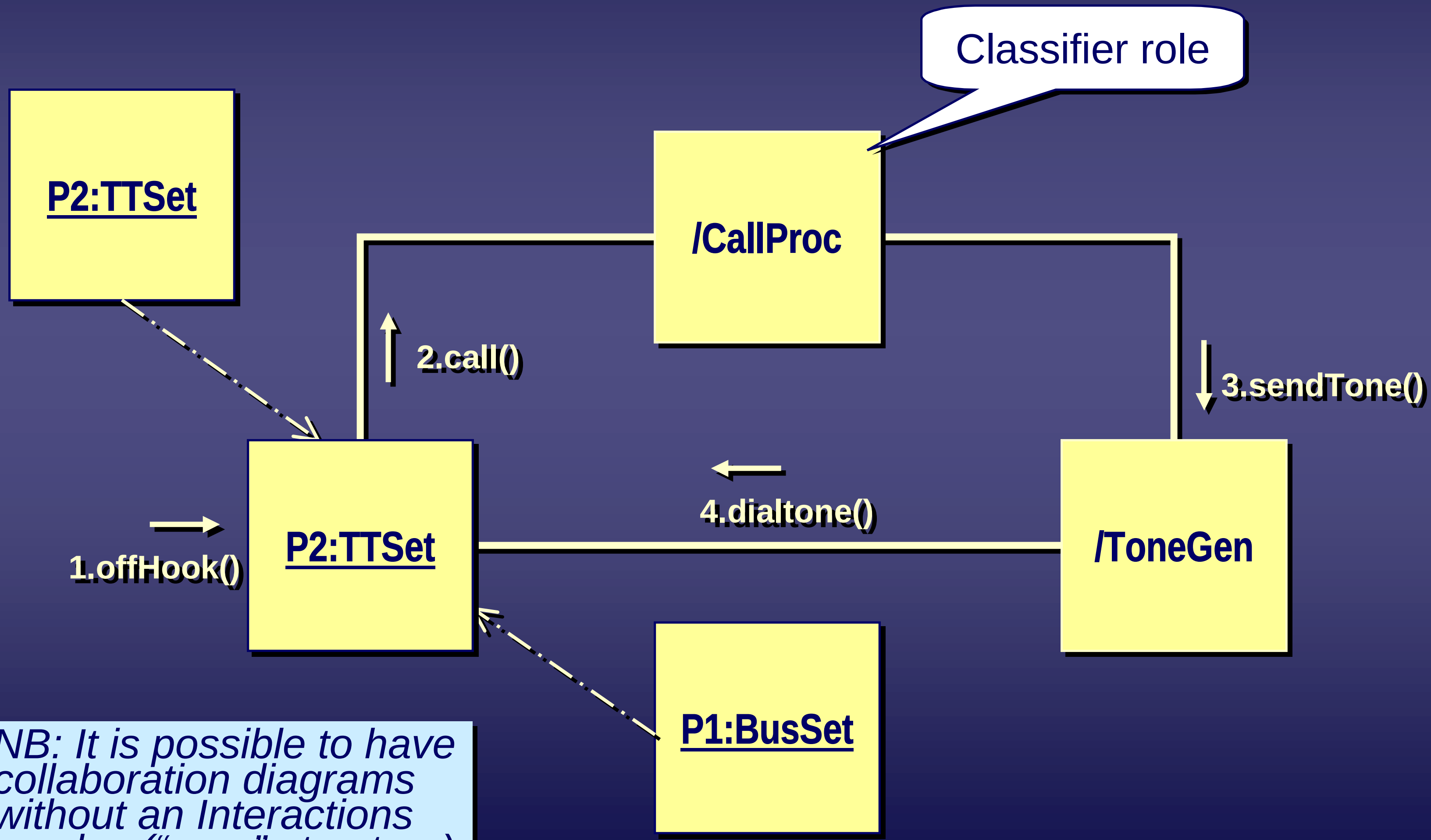


Object Diagrams to the Rescue?

- 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

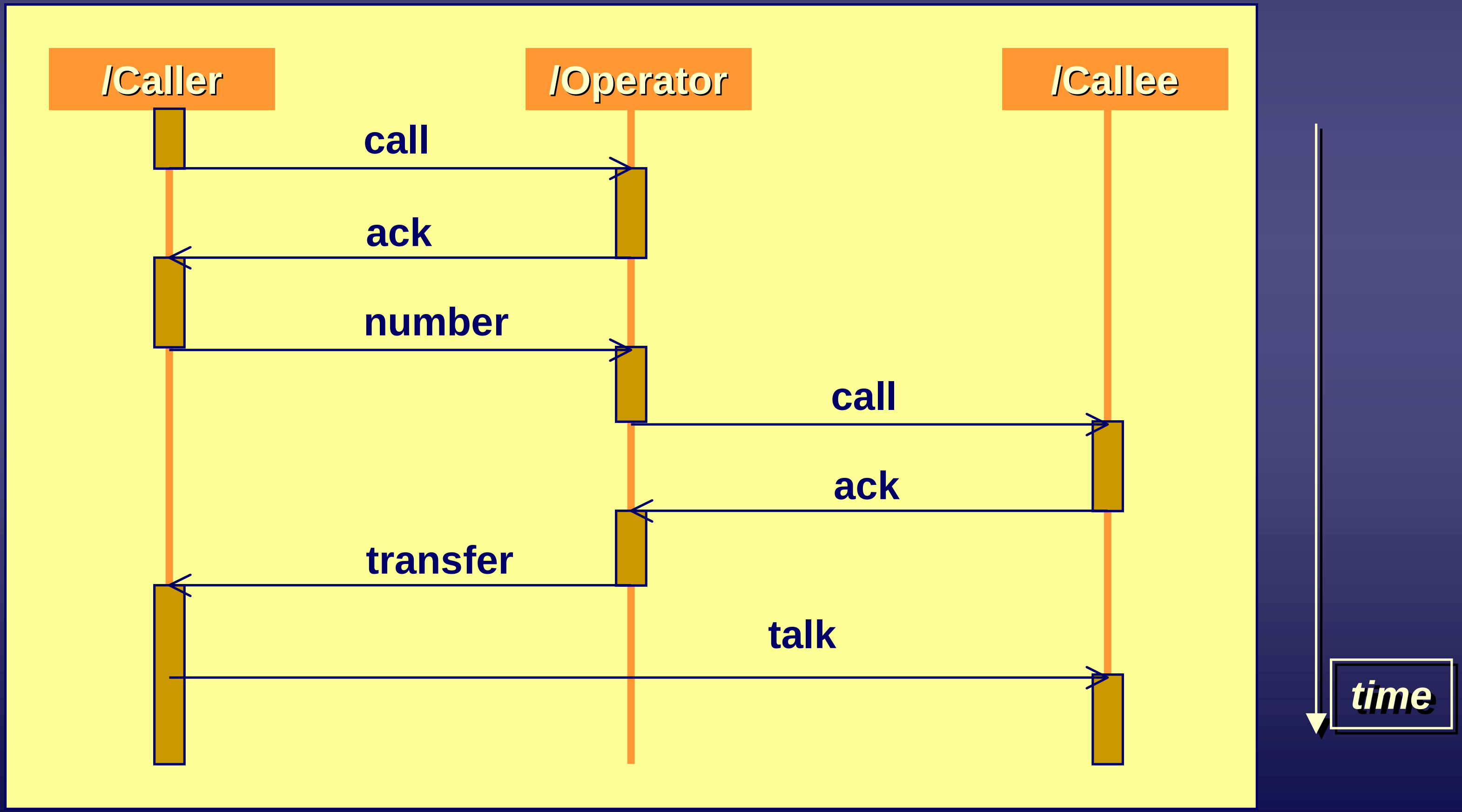
- Depict generic structural and behavioral patterns



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)

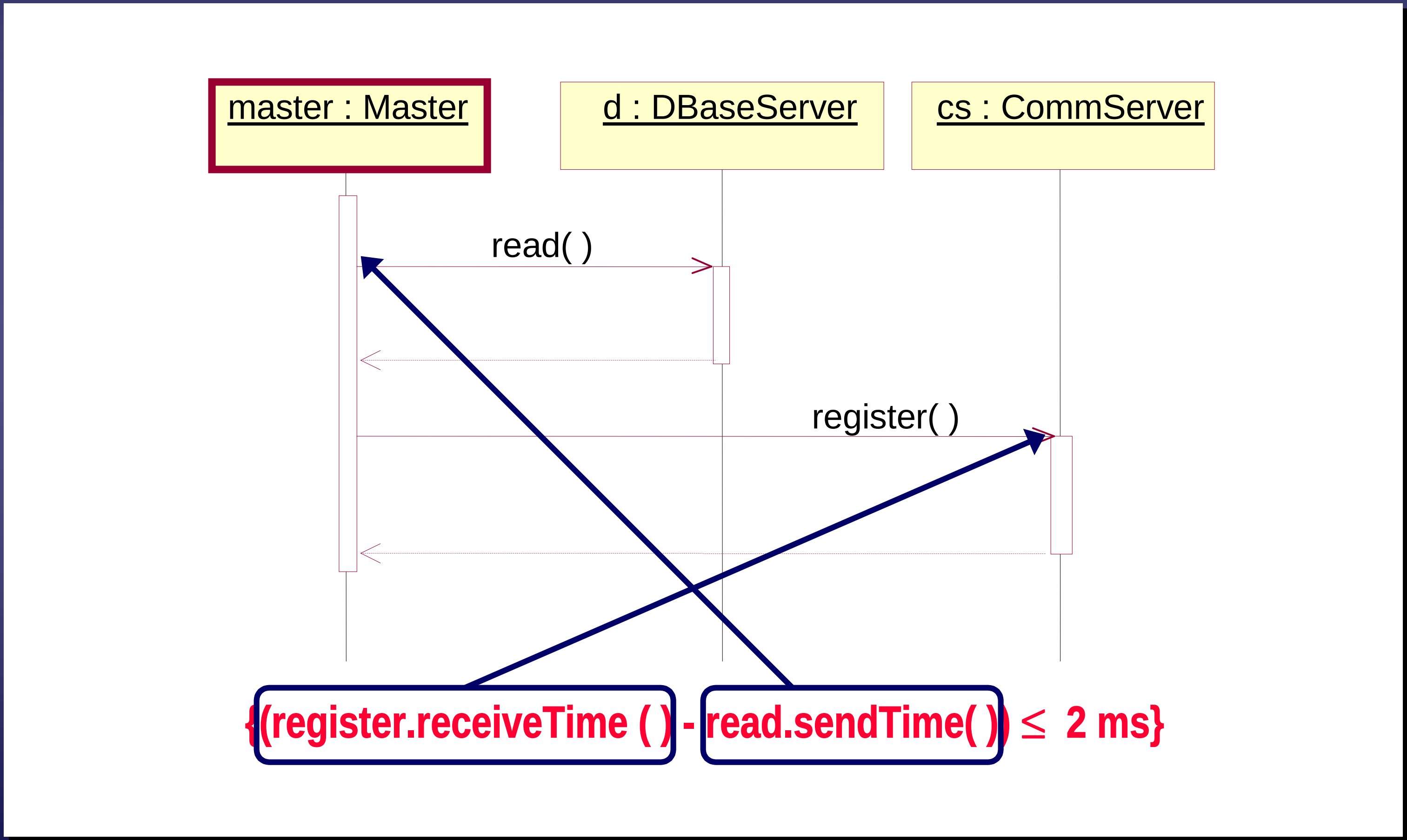


Sequence Diagrams and RT Systems

- 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

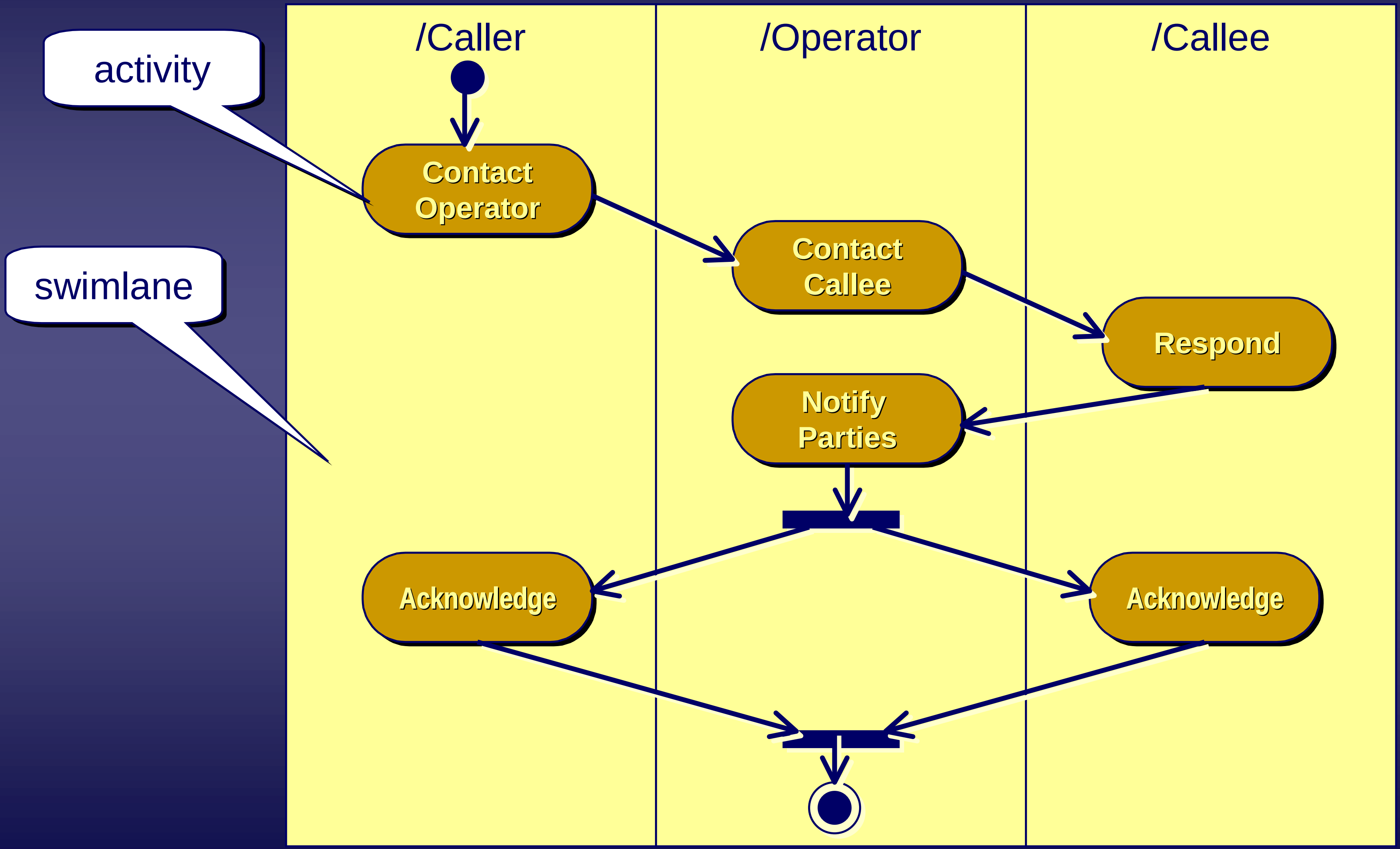
Using Timing Marks with Sequence Diagrams

- Specifying constraints



Activity Diagrams

- Different focus compared to sequence diagrams

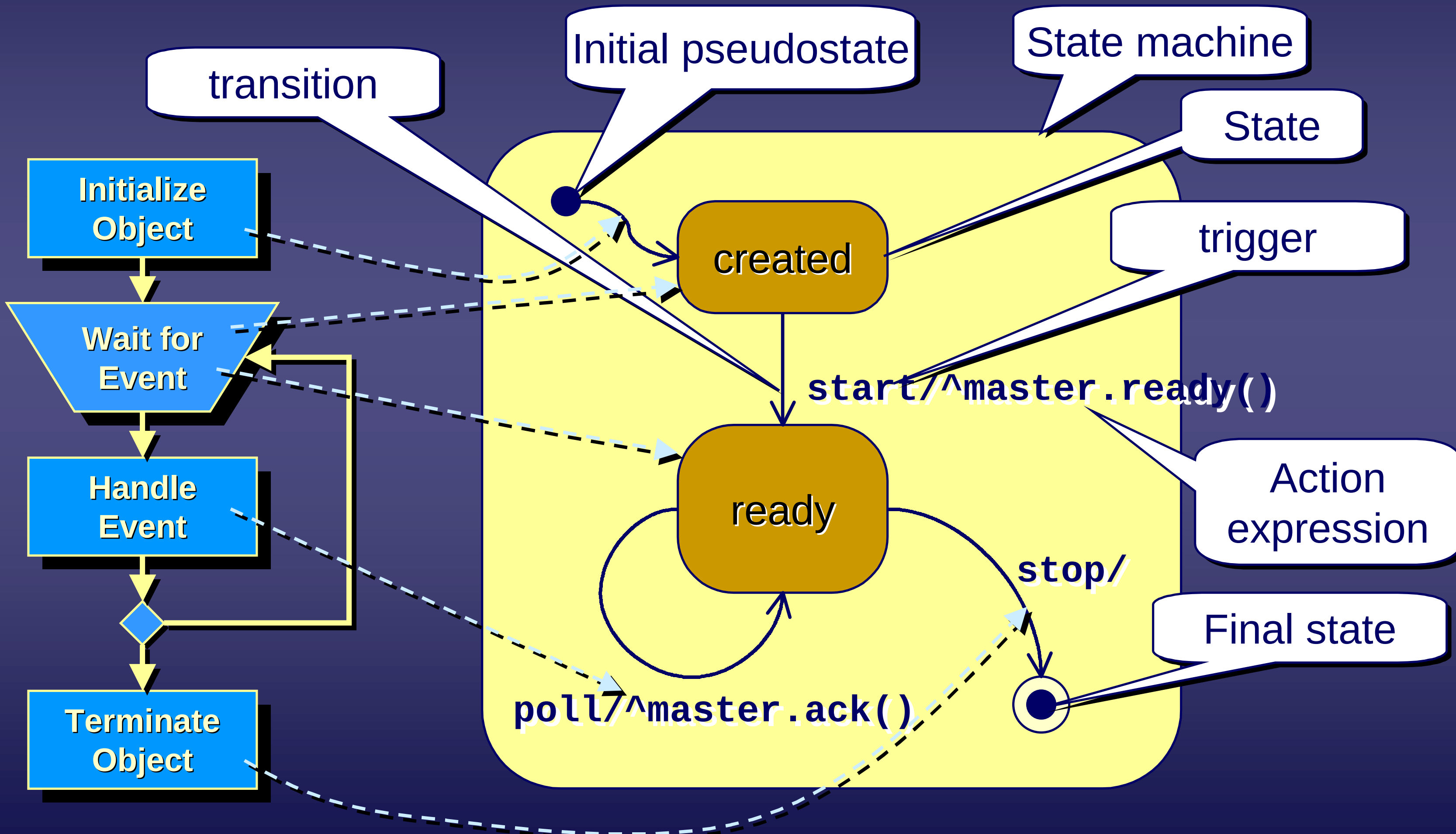


Activity Diagrams and RT Systems

- 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

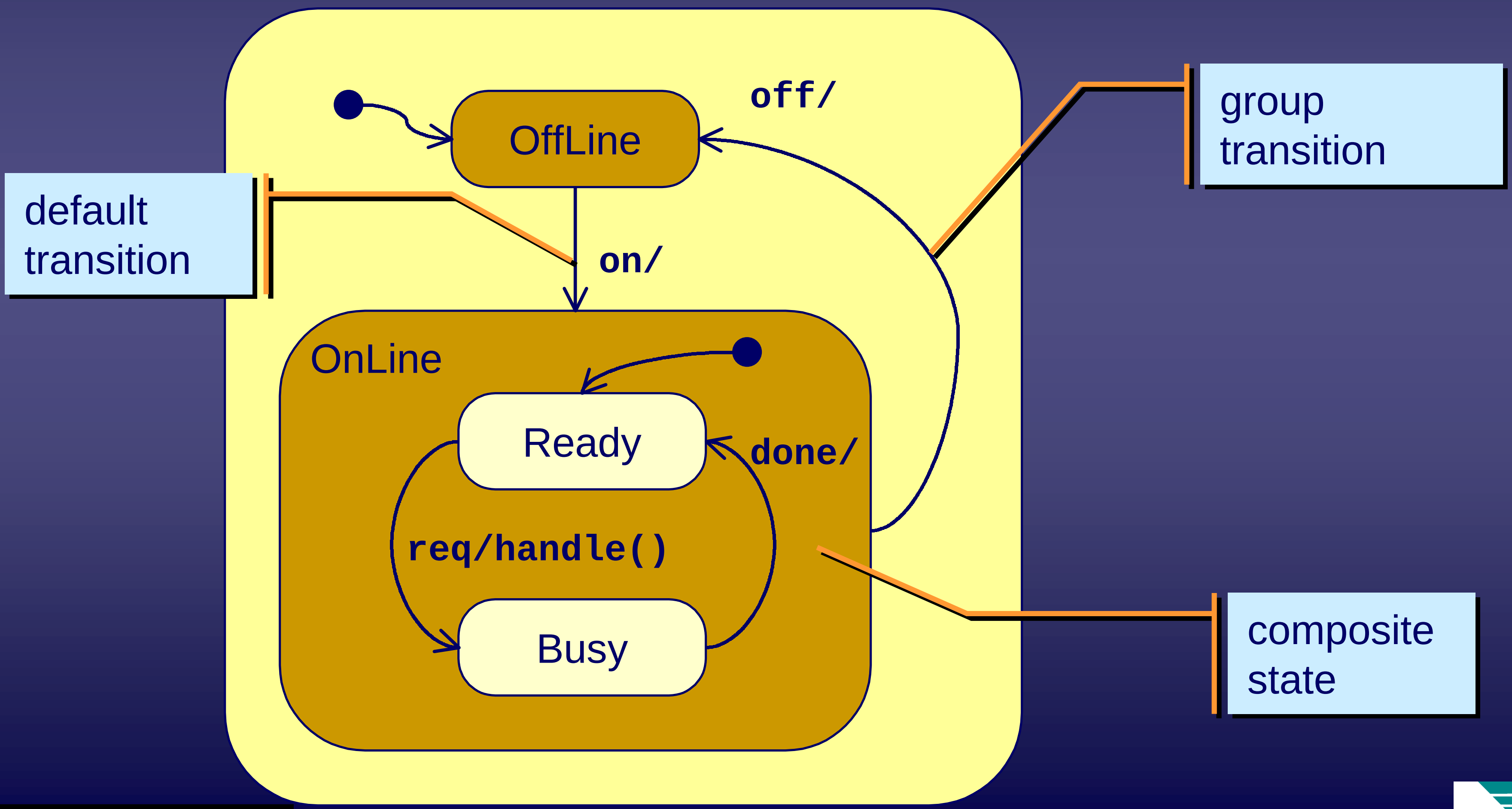
State Machine Diagram

- 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

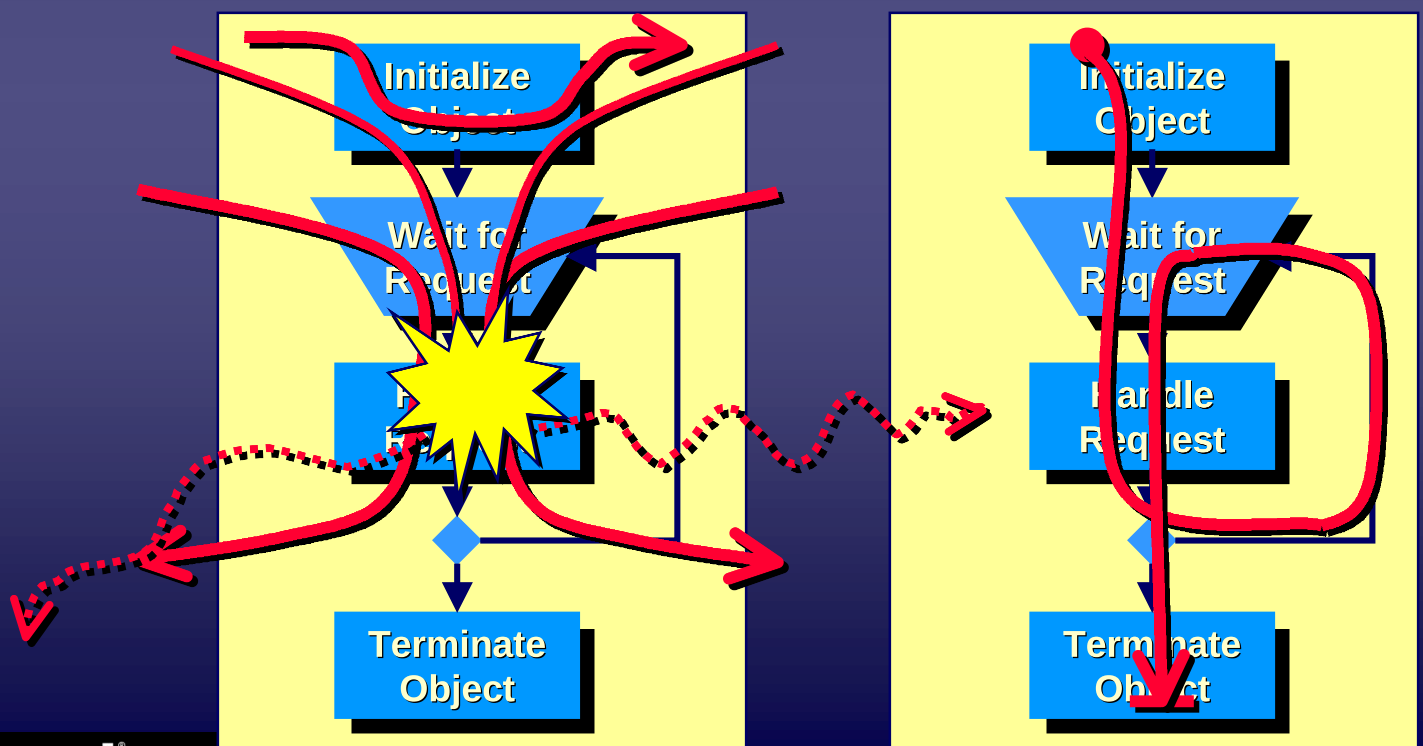
- Many real-time systems are event-driven
  - very well suited to those systems
  - scale up very nicely
- However…
  - not directly connected to time (except for time events)
  - e.g., run-to-completion paradigm

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

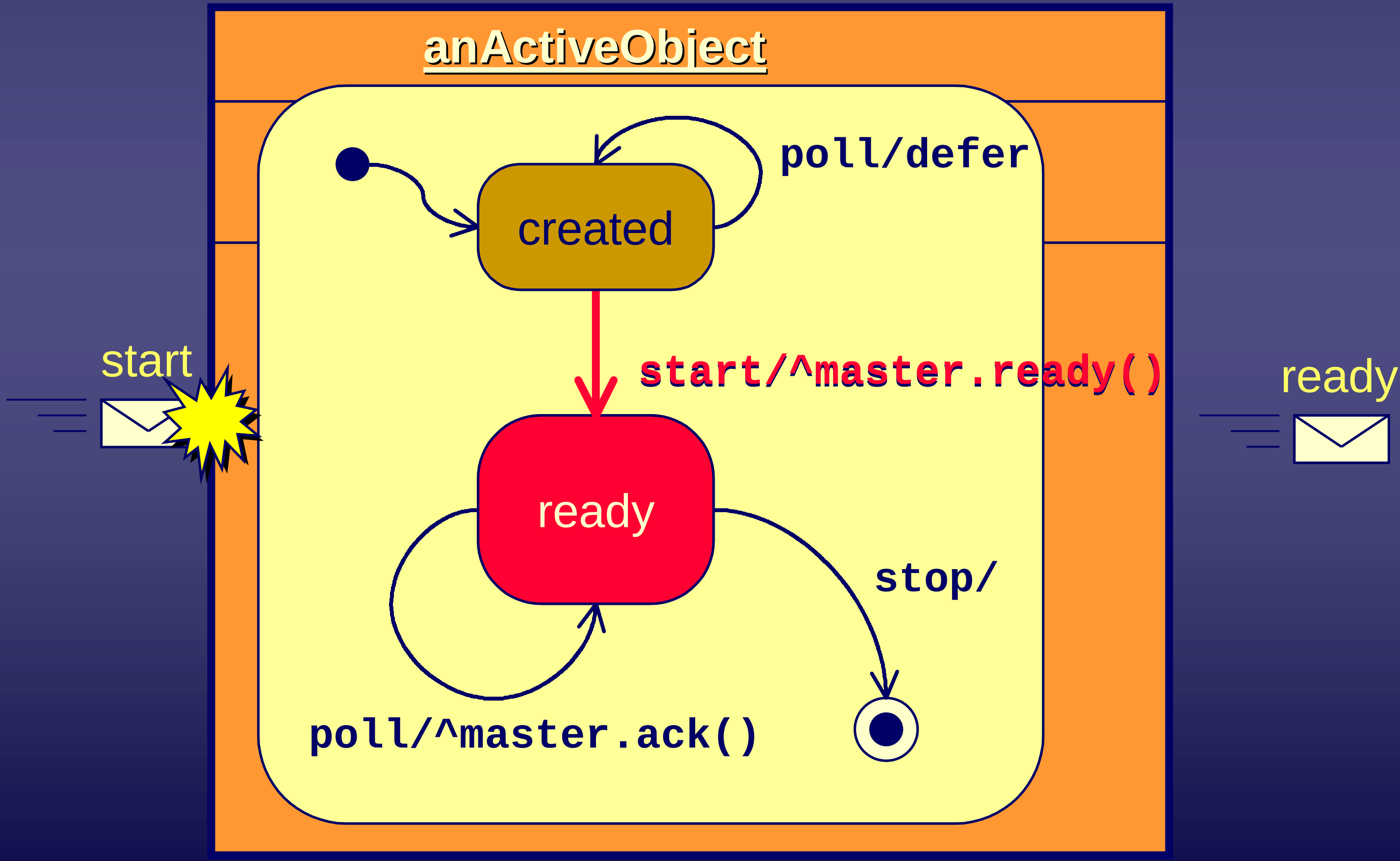
Objects and Concurrency

- *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



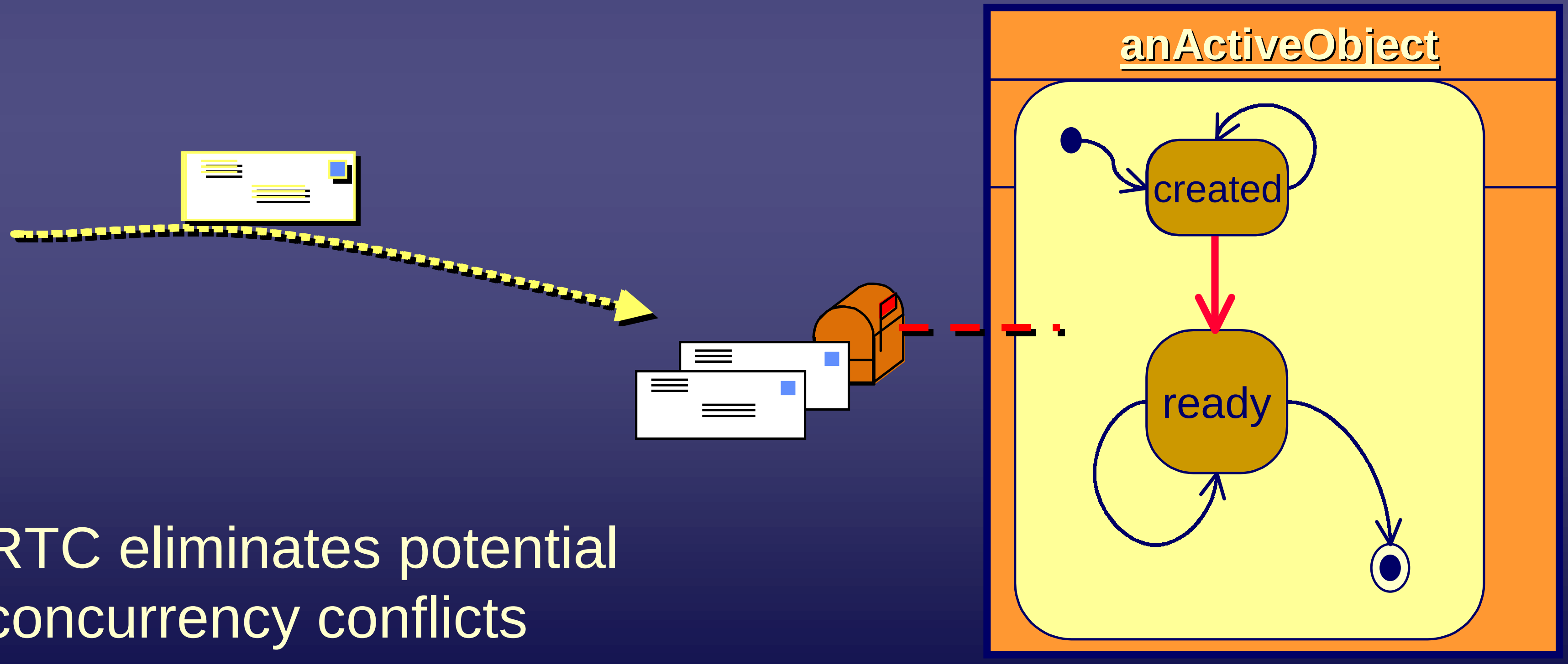
The Active Objects of UML

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



Active Object Semantics

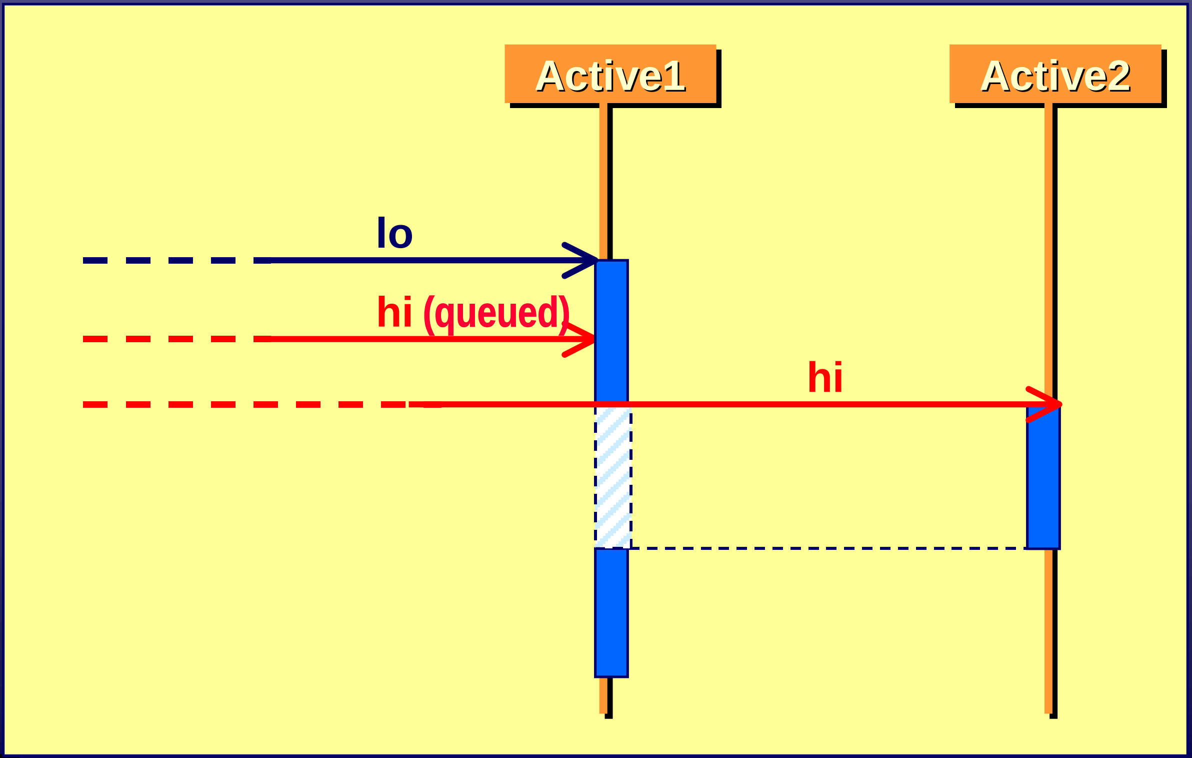
- Concurrent incoming events are queued and handled one-at-a-time regardless of priority
- *run-to-completion* (RTC) execution model



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

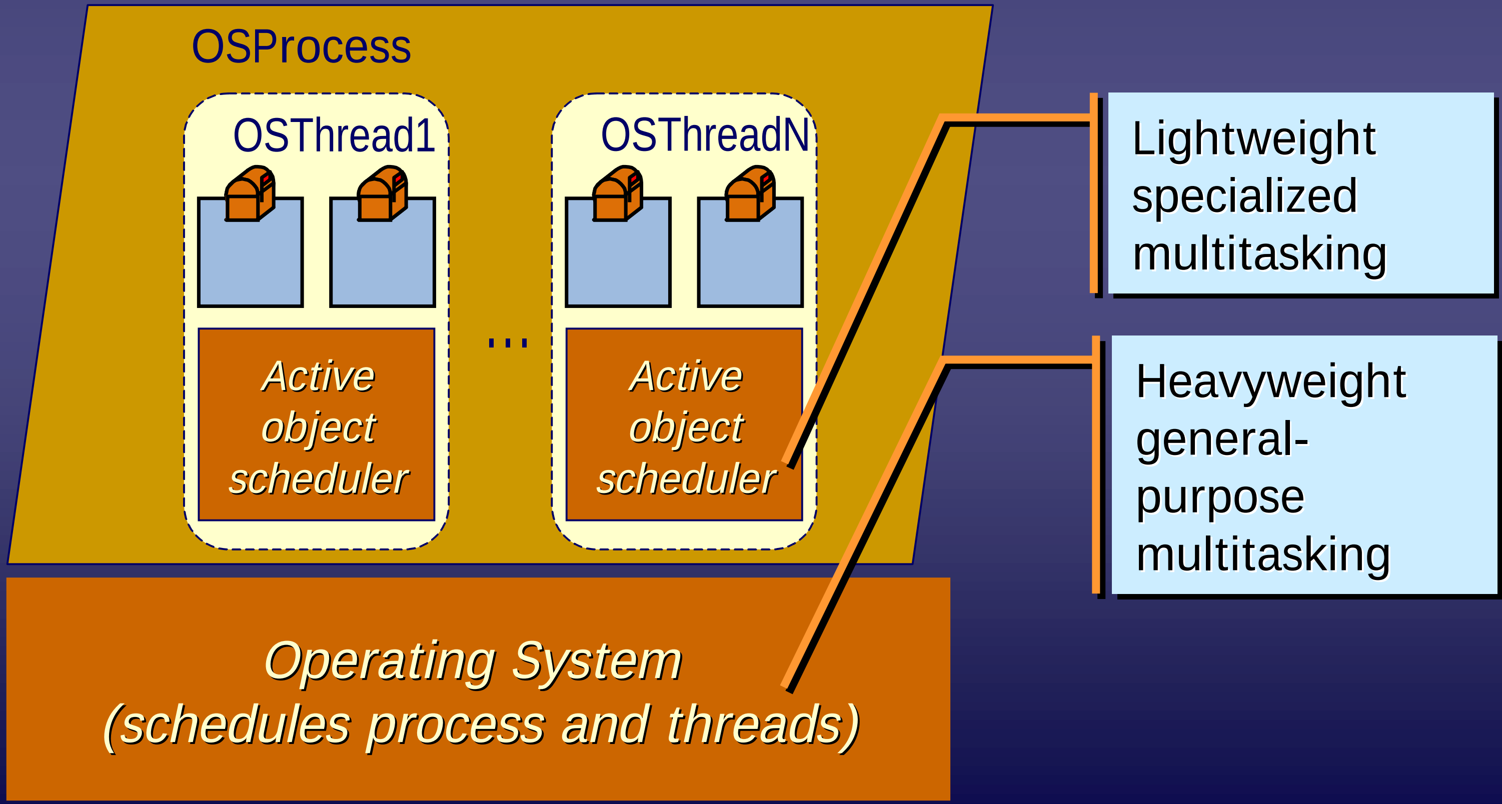


RTC Analysis

- 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

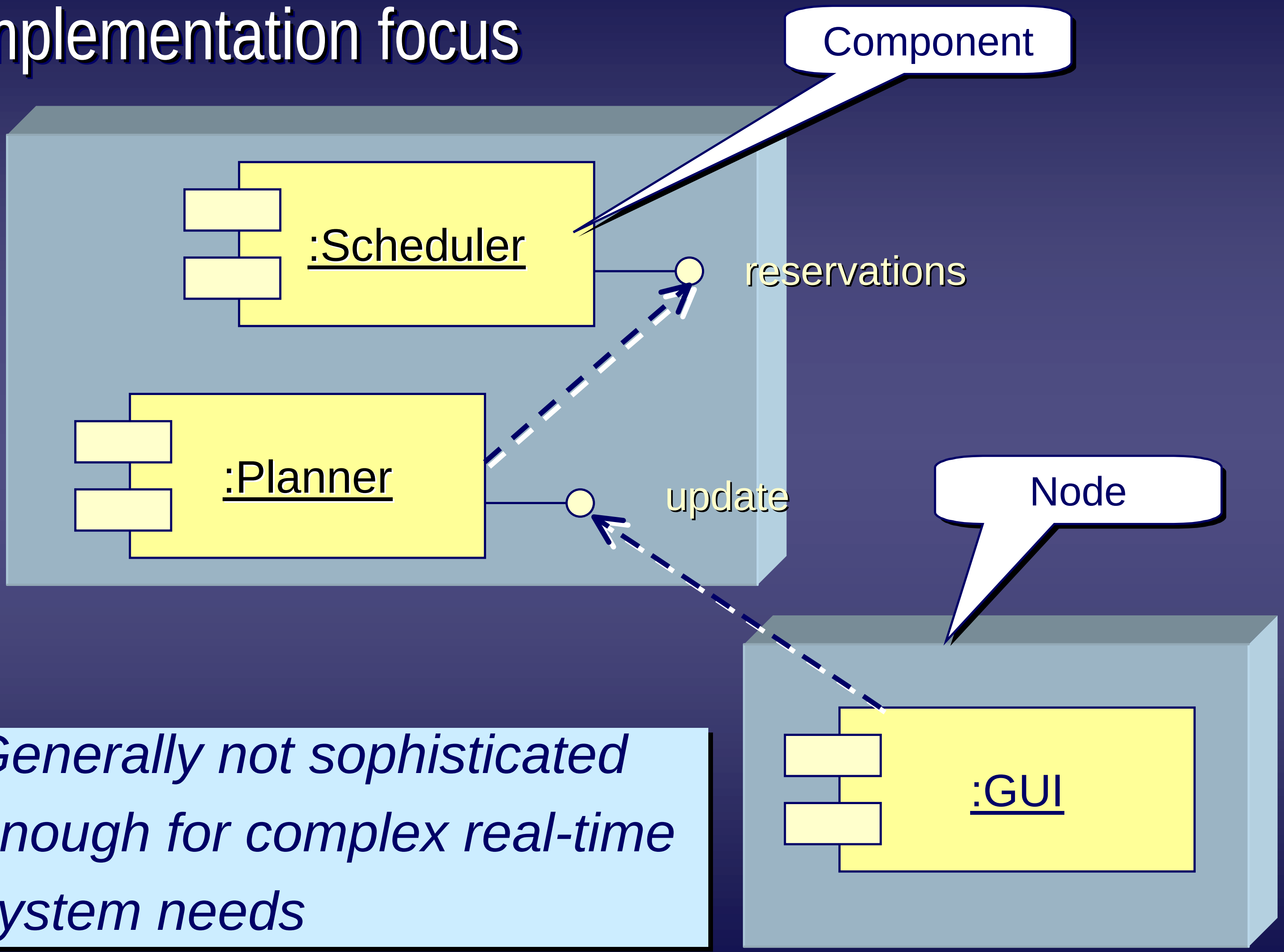
- Scheduling approach undefined
  - Hints of event-based priorities (versus thread-based)
  - Timing events allow realization of time-triggered systems
- The actual scheduling policy is unspecified
  - A *semantic variation point*
  - Can be customized to suit application requirements

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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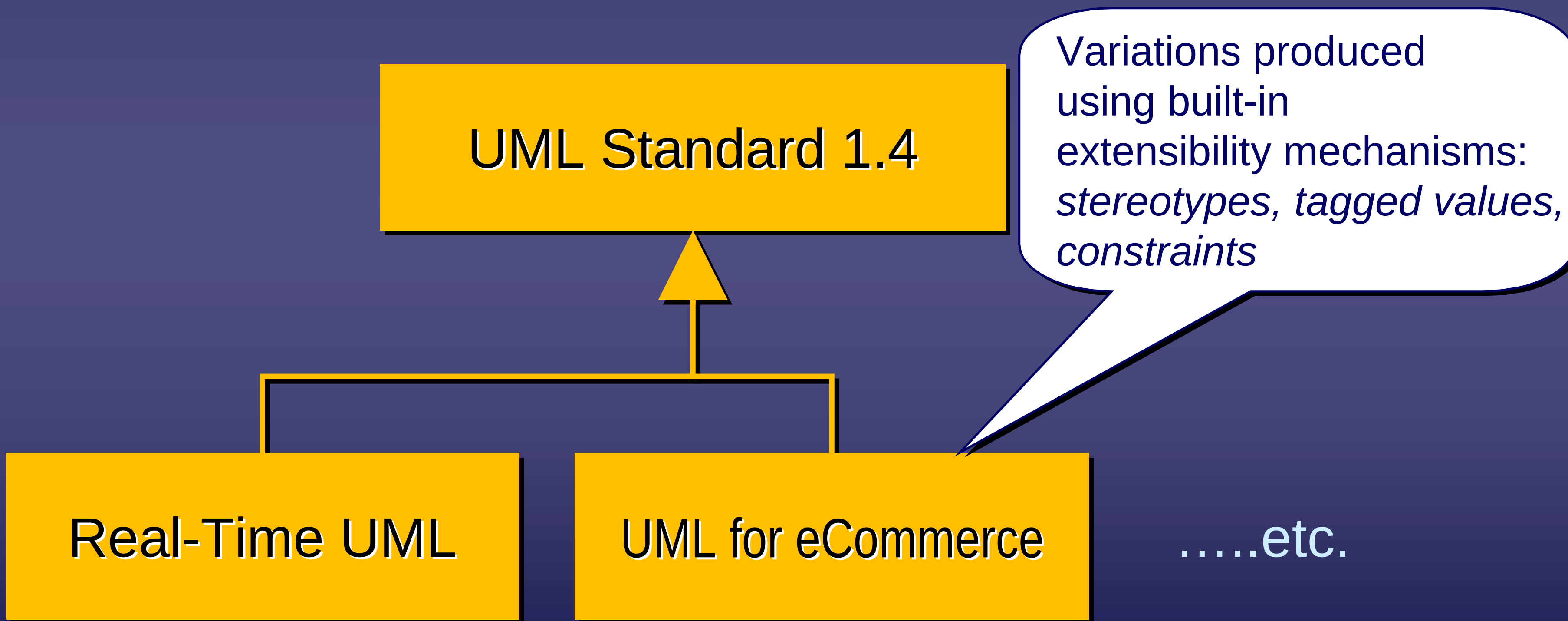
Semantic Variation in UML

- 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

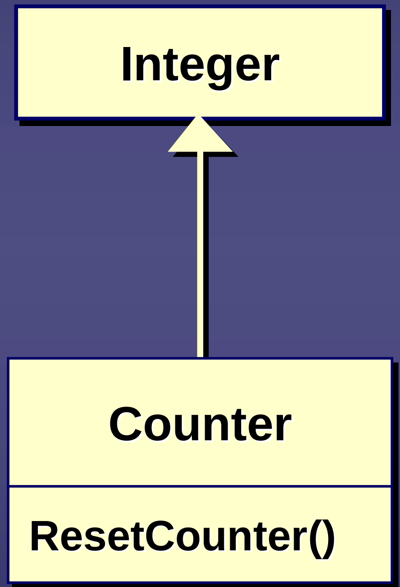
Specialization of UML

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



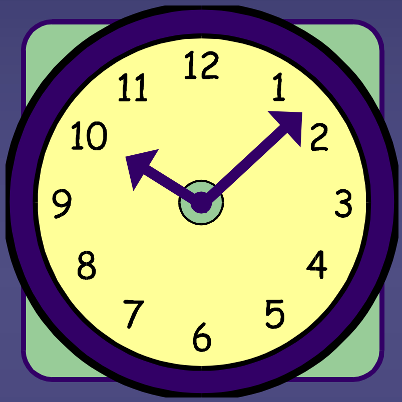
How Do We Specialize UML?

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



Specialization through regular inheritance

But, how can we specify a clock?

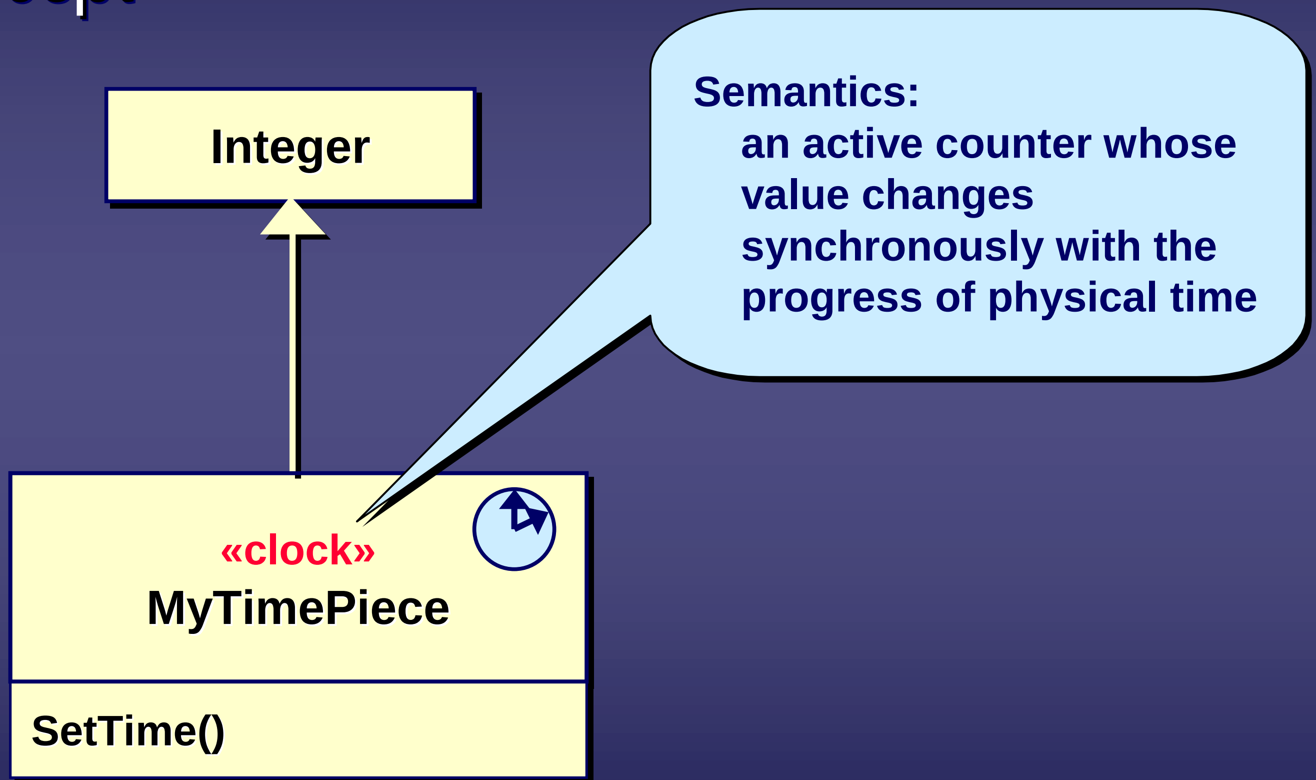


Semantics:

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

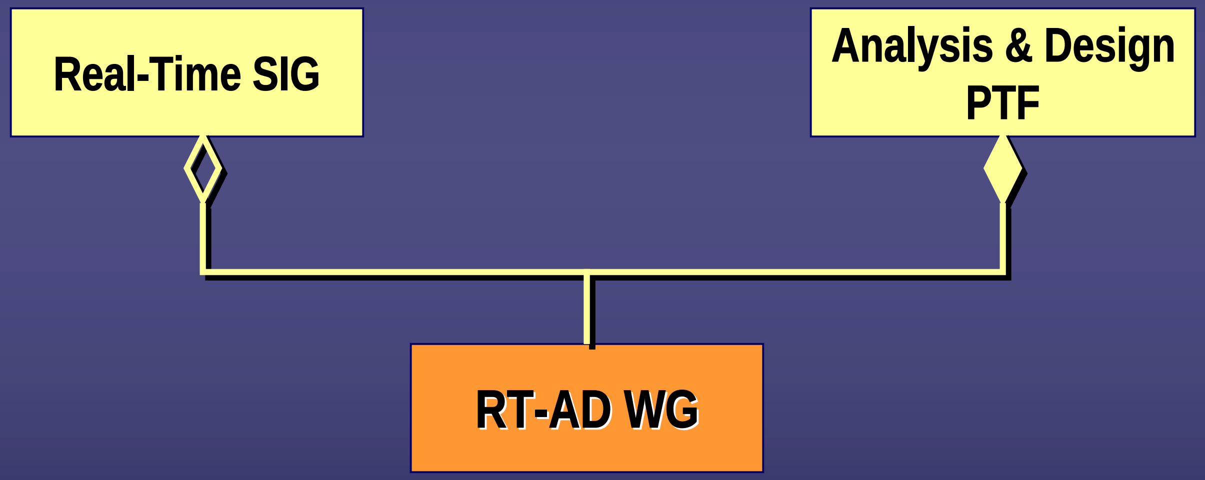
- A package of related specializations of general UML concepts that capture domain-specific variations and usage patterns
  - *A domain-specific interpretation of UML*
- Fully conformant with the UML standard
  - additional semantic constraints cannot contradict the general UML semantics
  - within the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

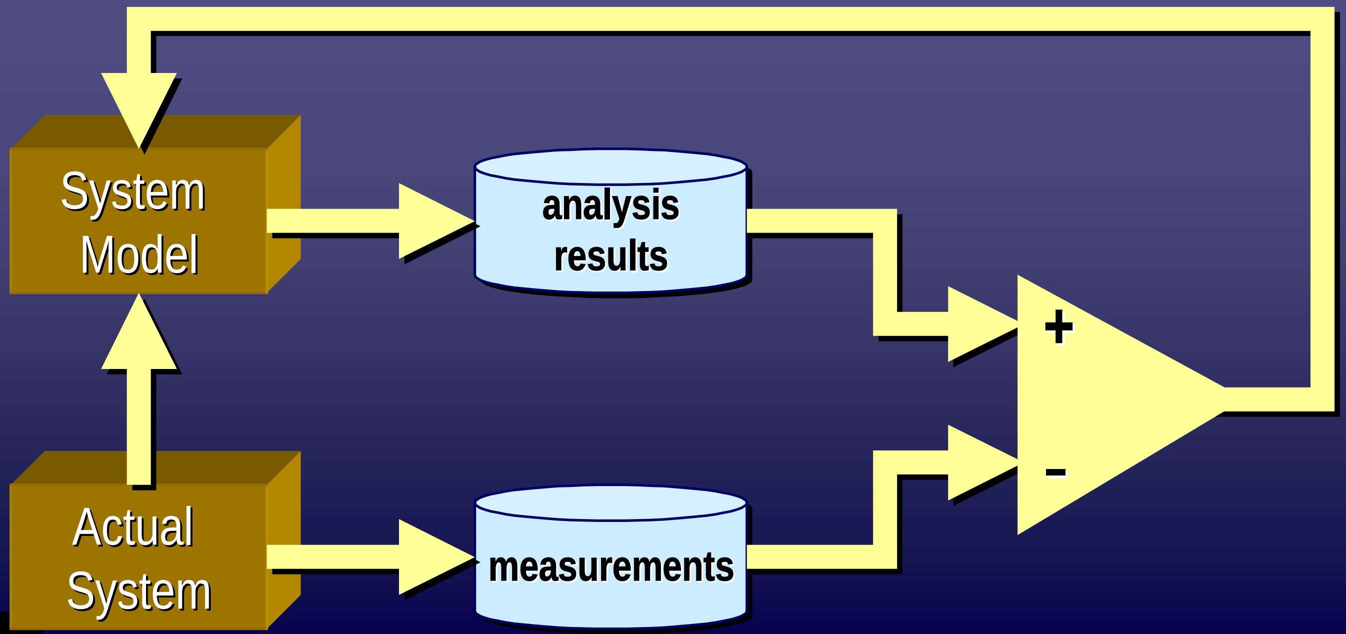
- Once we have included QoS information in our models, we can use *quantitative methods* to:
  - predict system characteristics (detect problems early)
  - analyze existing system
  - synthesize elements of the model
- Methods considered for the profile:
  - Schedulability analysis

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

    what kind of response will the system have under load?

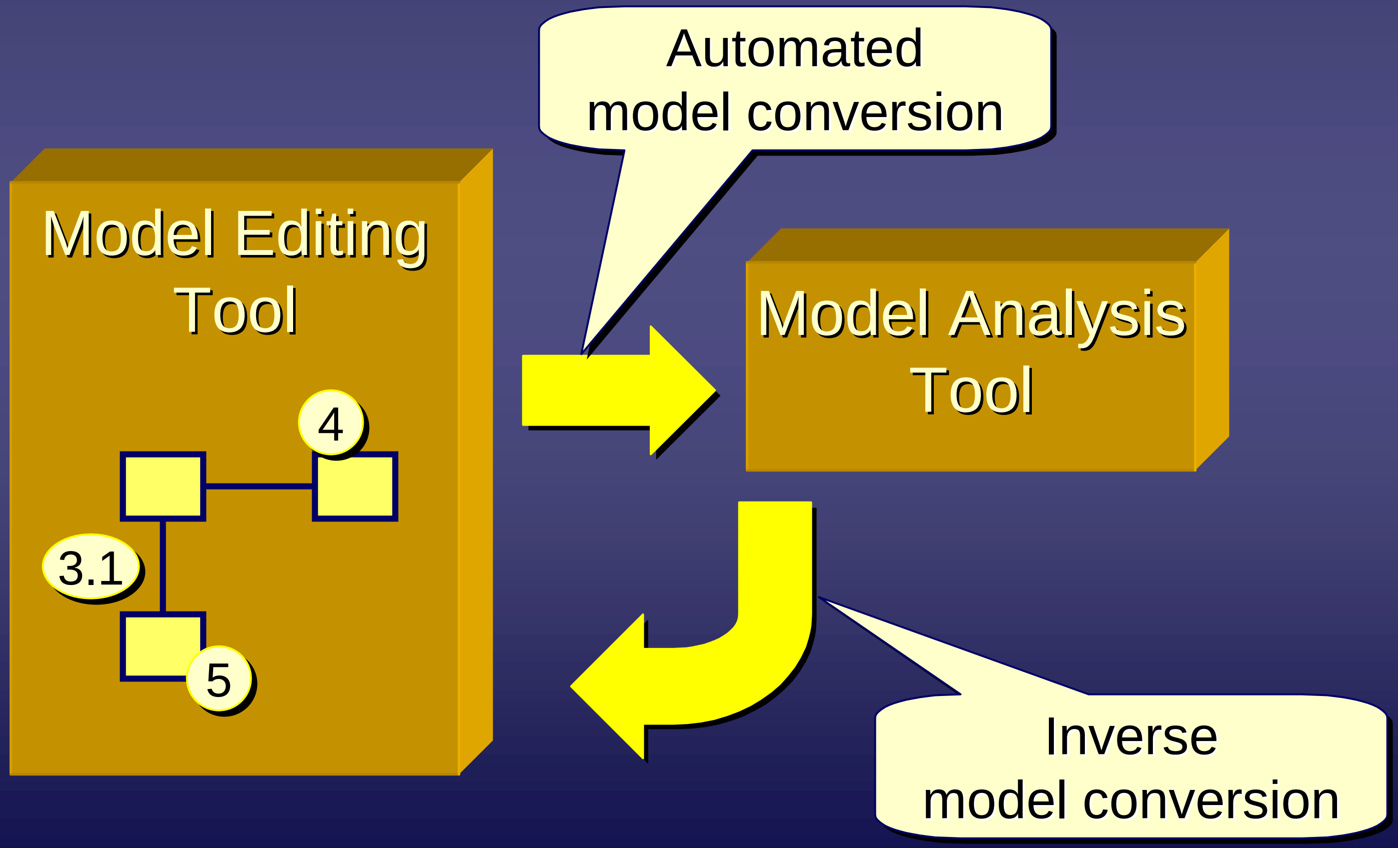
Issues with Quantitative Methods

- 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:

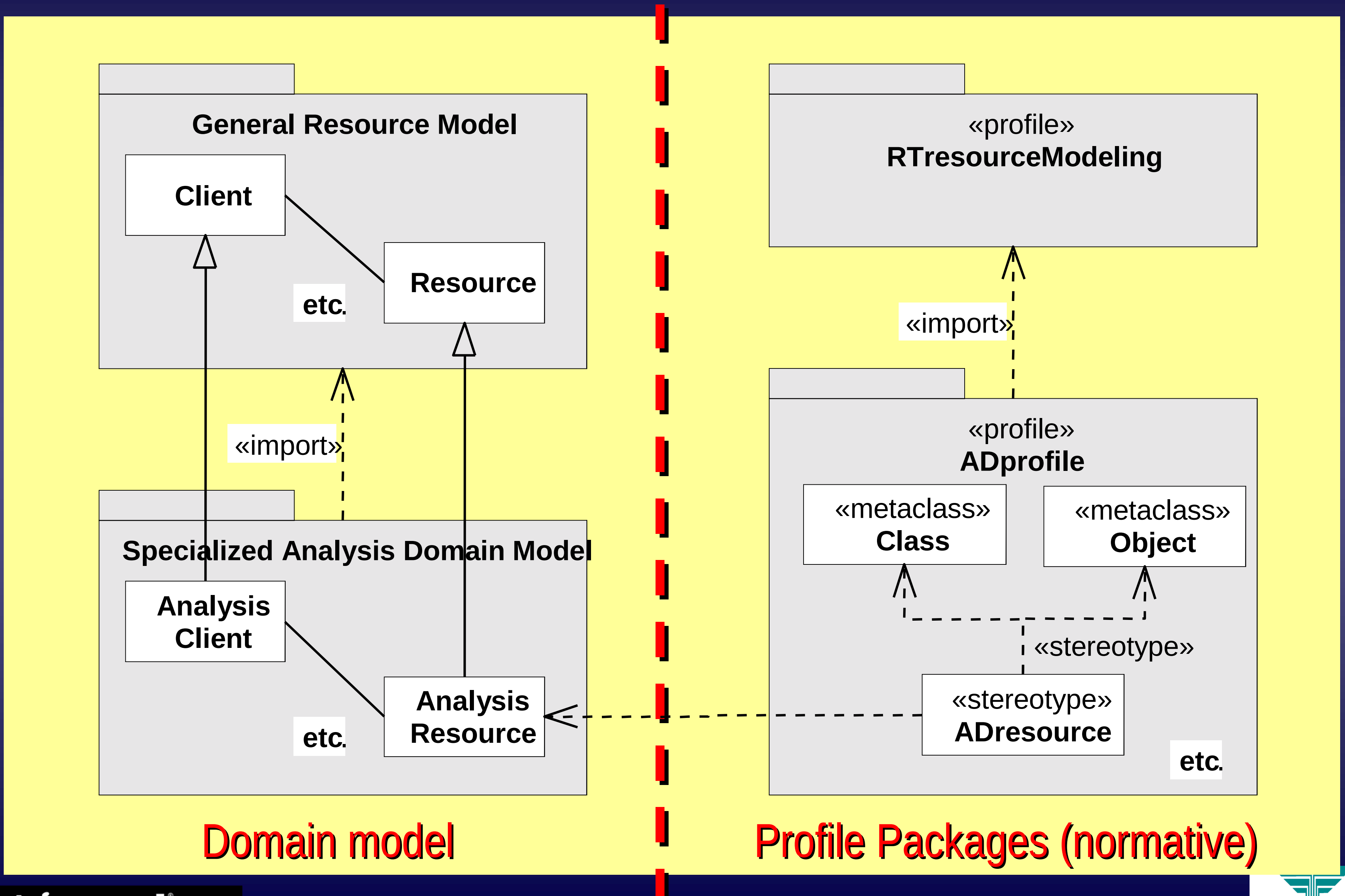


Desired Development Model

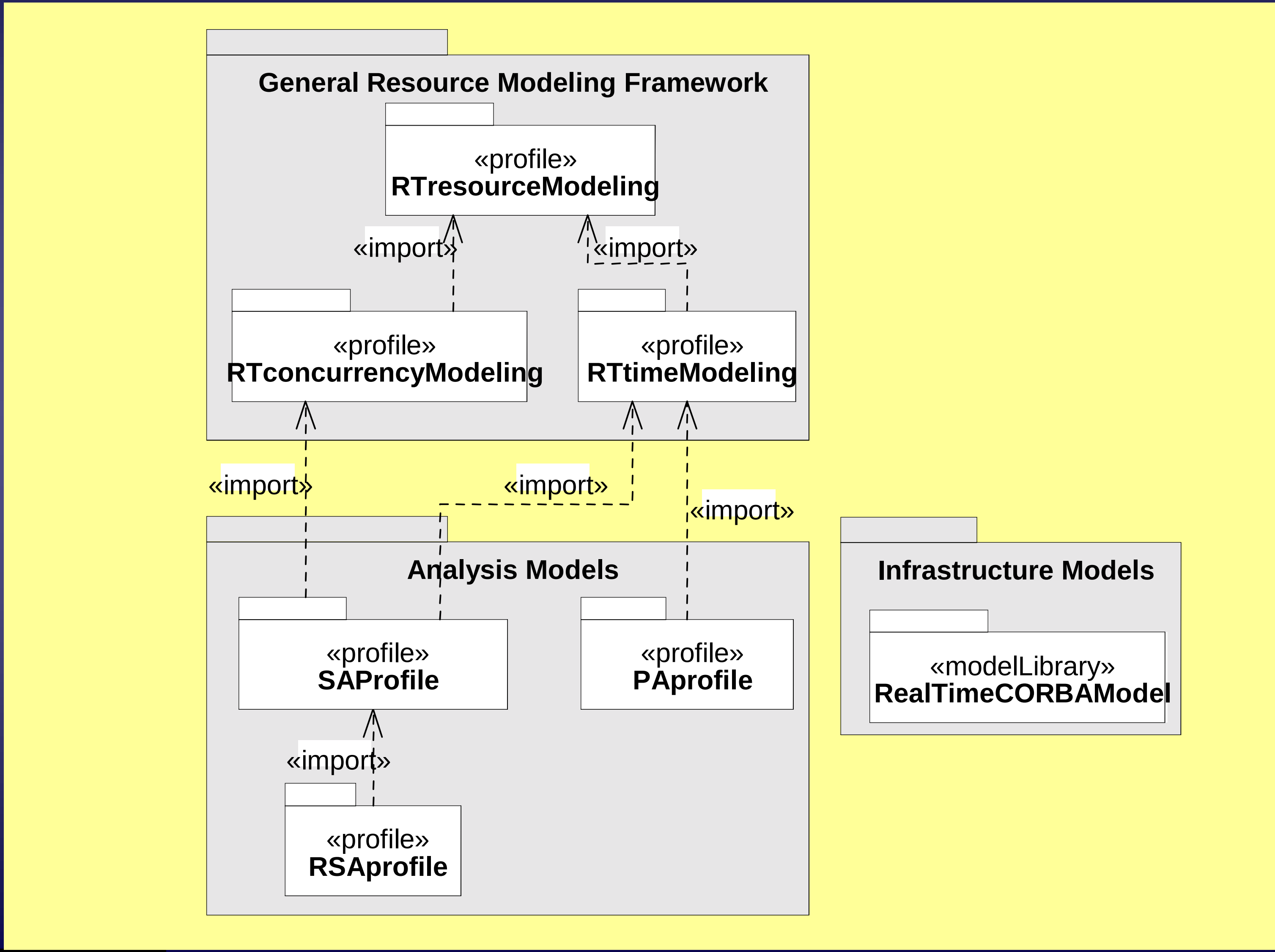
- Seamless integration of technologies and tools based on standards for real-time modeling



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

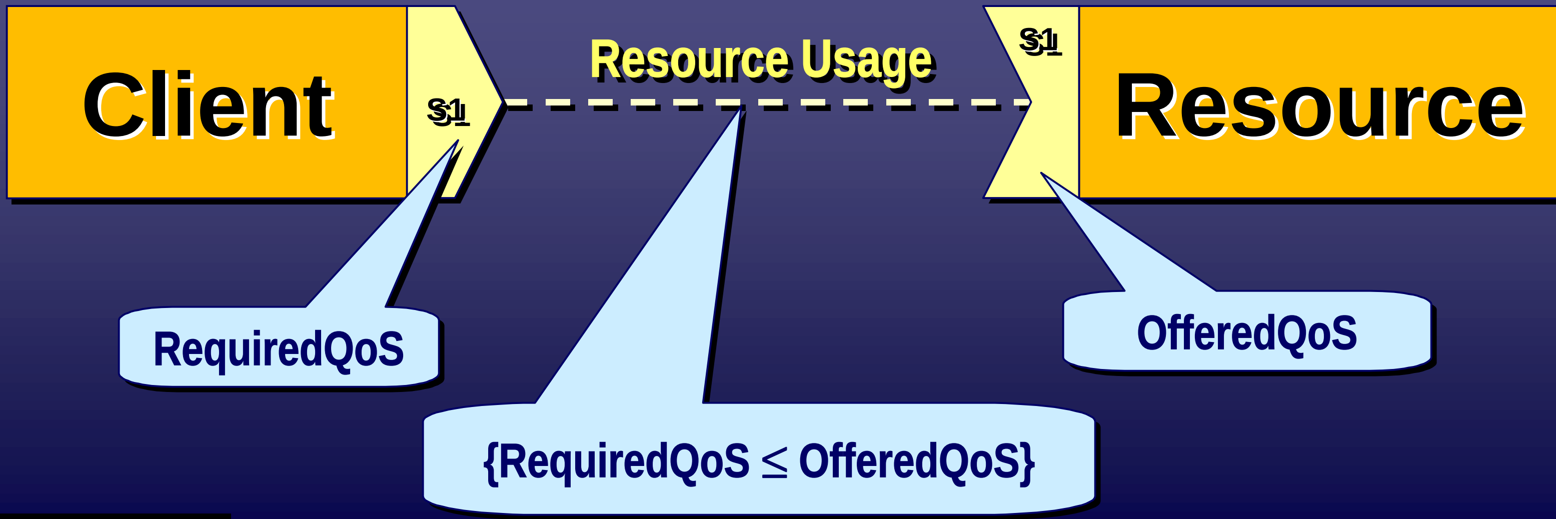
  - e.g. throughput, capacity, response time
- The specification of a model element can include:
  - *offered QoS:* the QoS that it provides to its clients
  - *required QoS:* the QoS it requires from other components to support its QoS obligations

Resources and Quality of Service

- Resource:

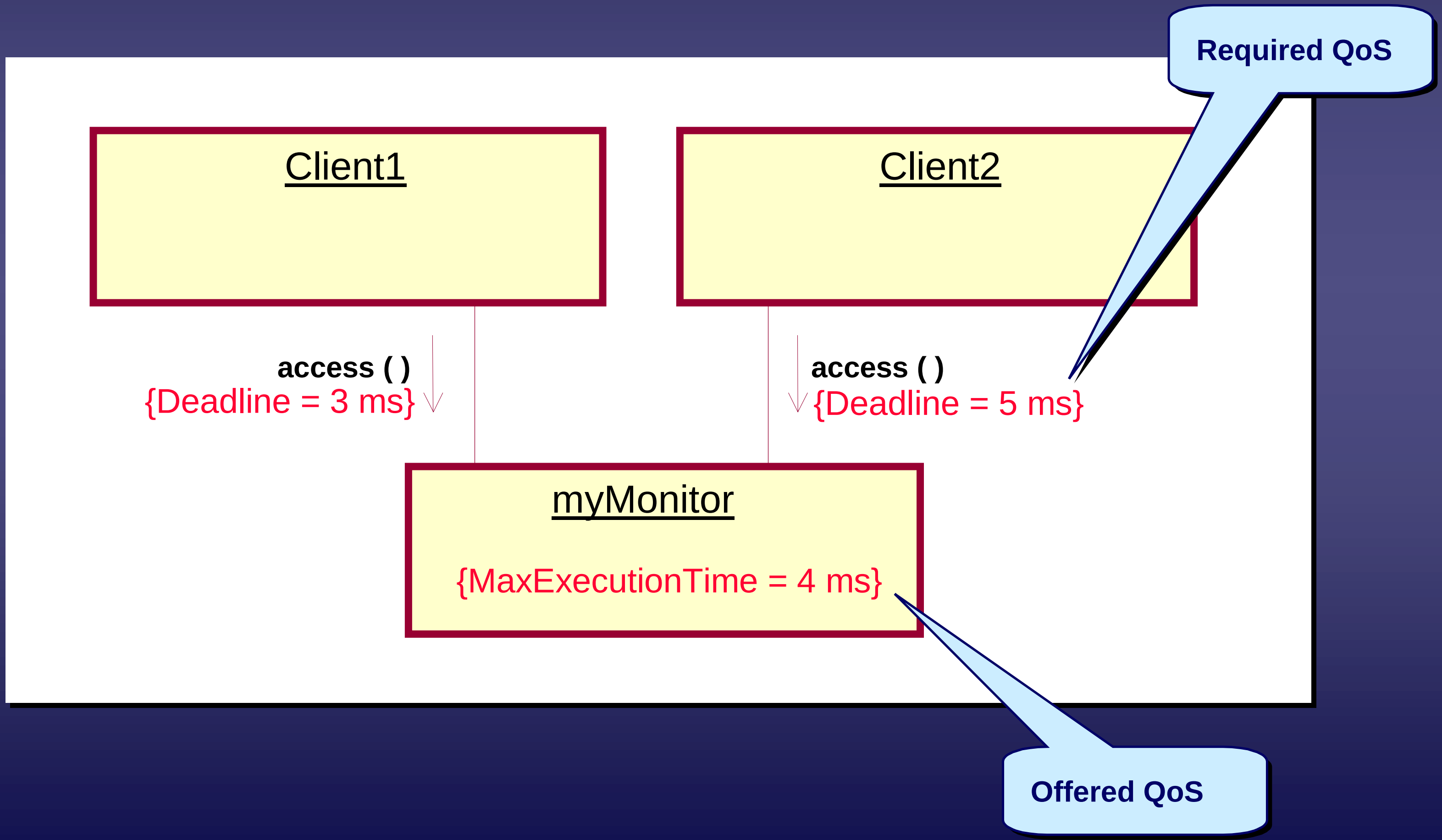
  an element whose service capacity is limited, directly or indirectly, by the finite capacities of the underlying physical computing environment

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

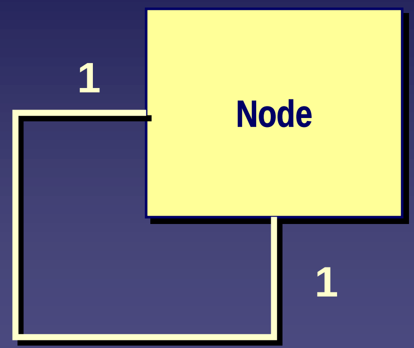


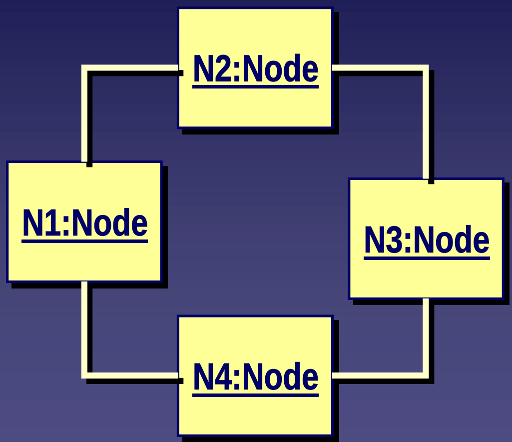
Simple Example

- Concurrent tasks accessing a monitor with known response time characteristics



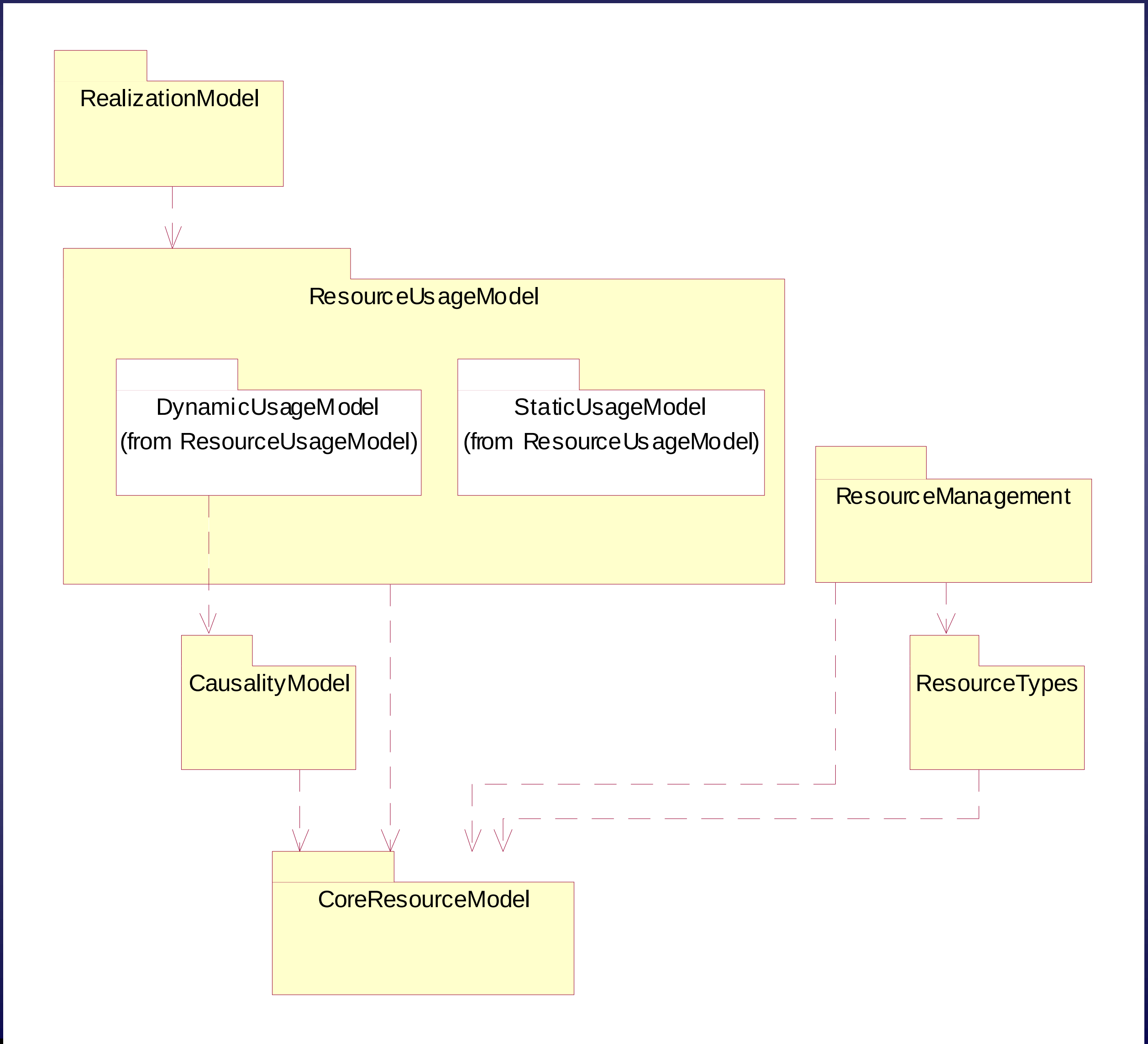
Instance- vs Class-Based Models



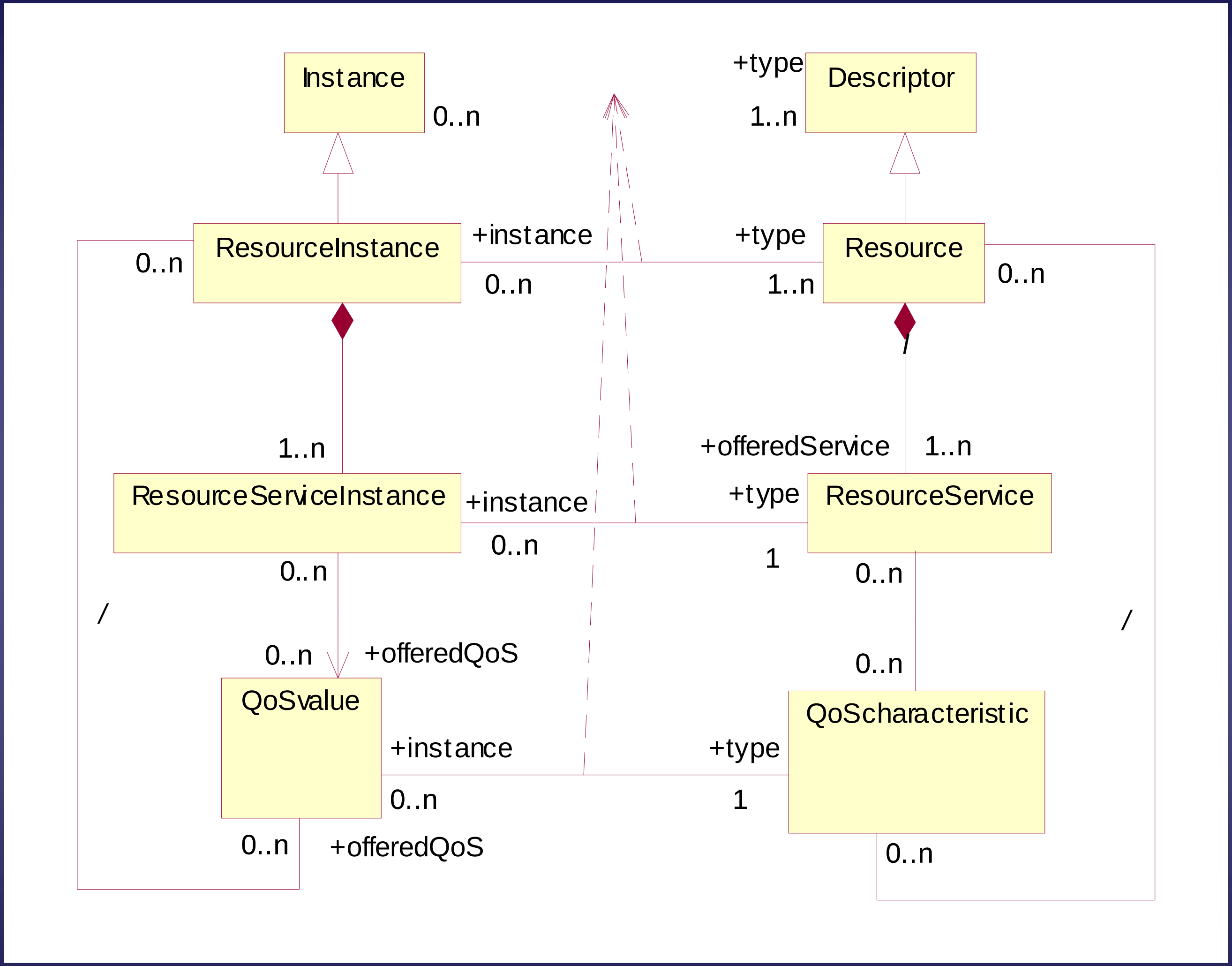


- Practically all analysis methods are concerned with instance-based models
- However, it is often useful to associate QoS characteristics with classes
  - Used to define default values that may be overridden for specific instances
- Need to apply a stereotype to both spec elements and instance elements

The General Resource Model

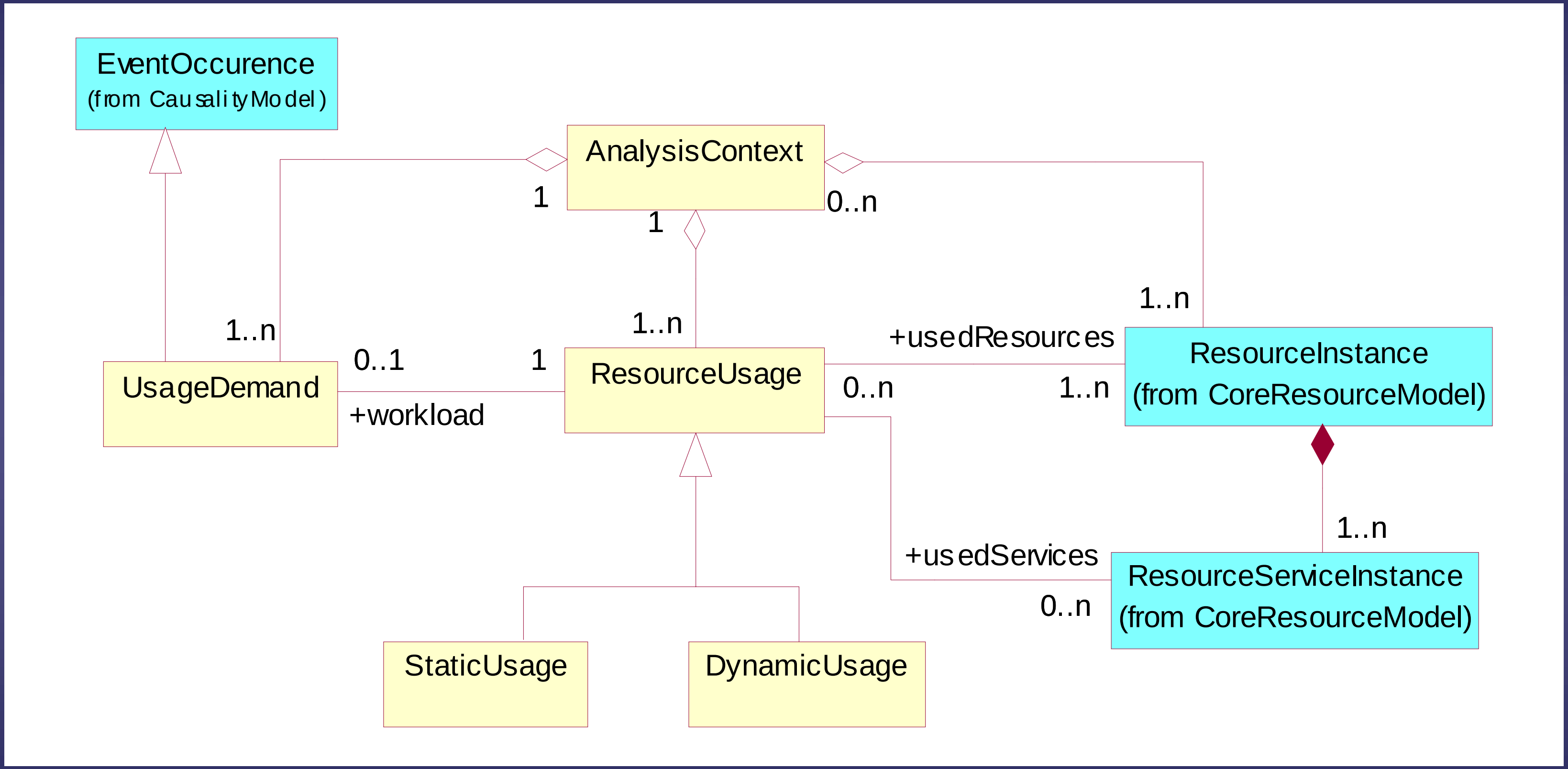


Core Resource Model



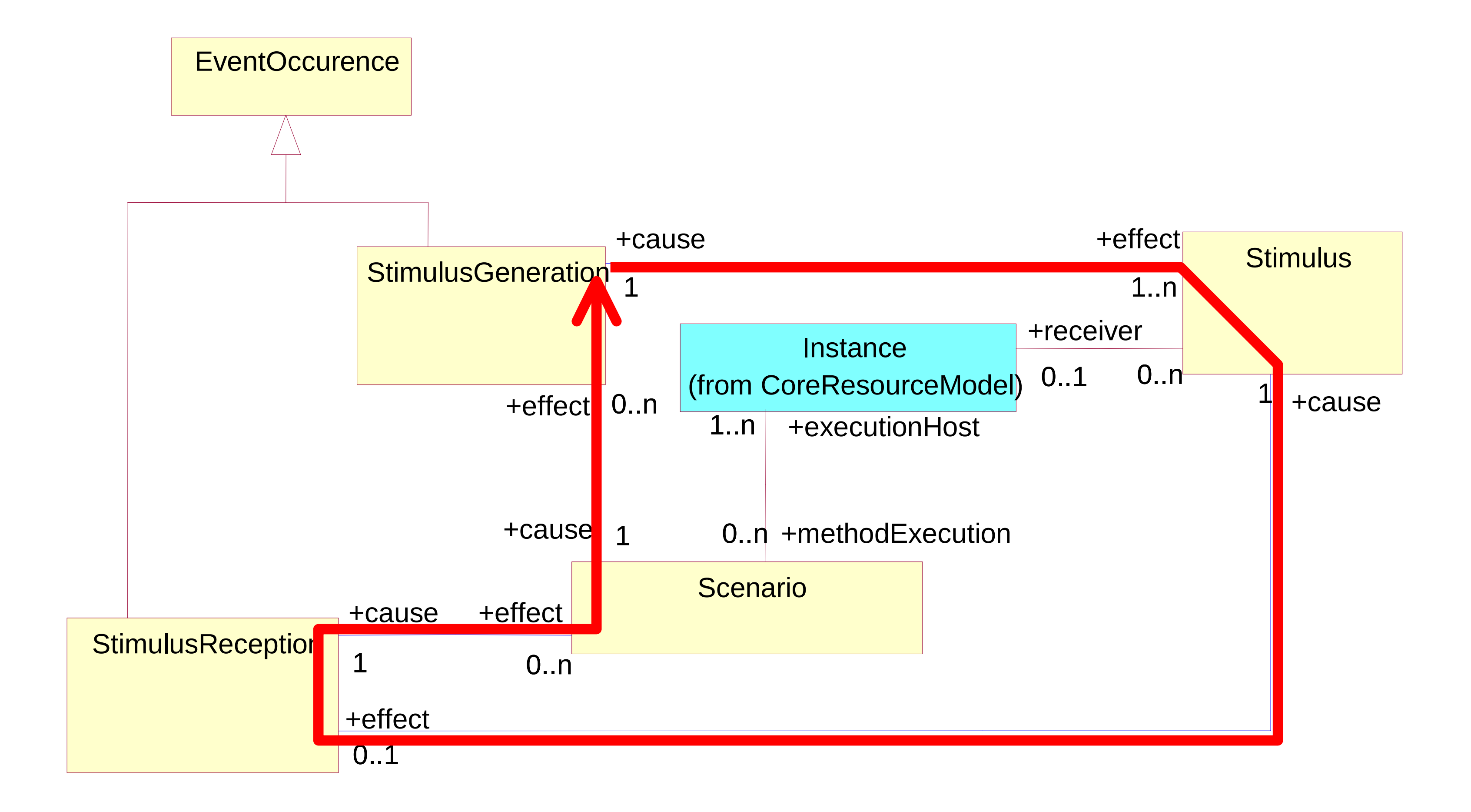
- NB: This is a model of the domain concepts
  - (i.e., it is not a UML metamodel)

Basic Resource Usage Model

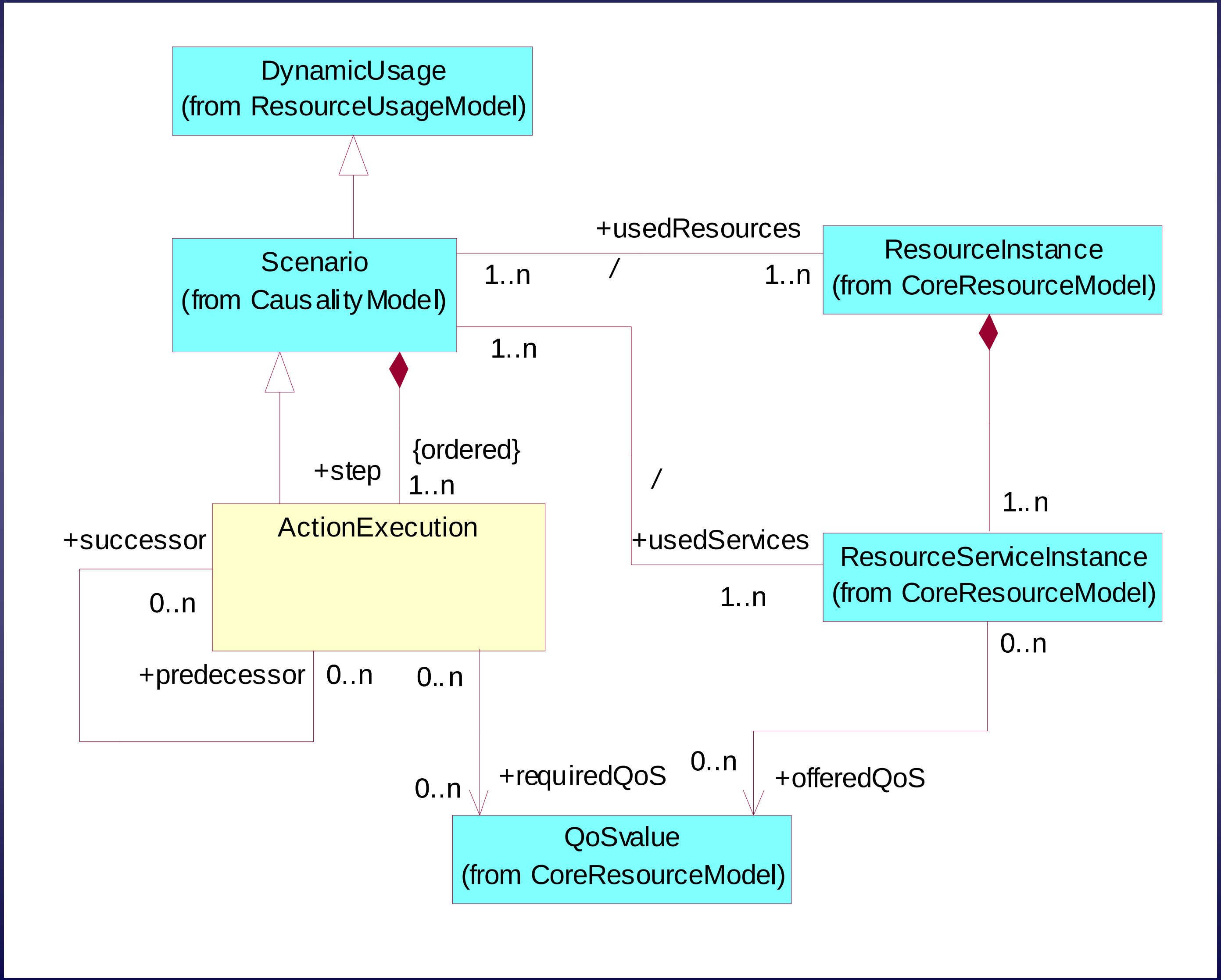


Basic Causality Loop

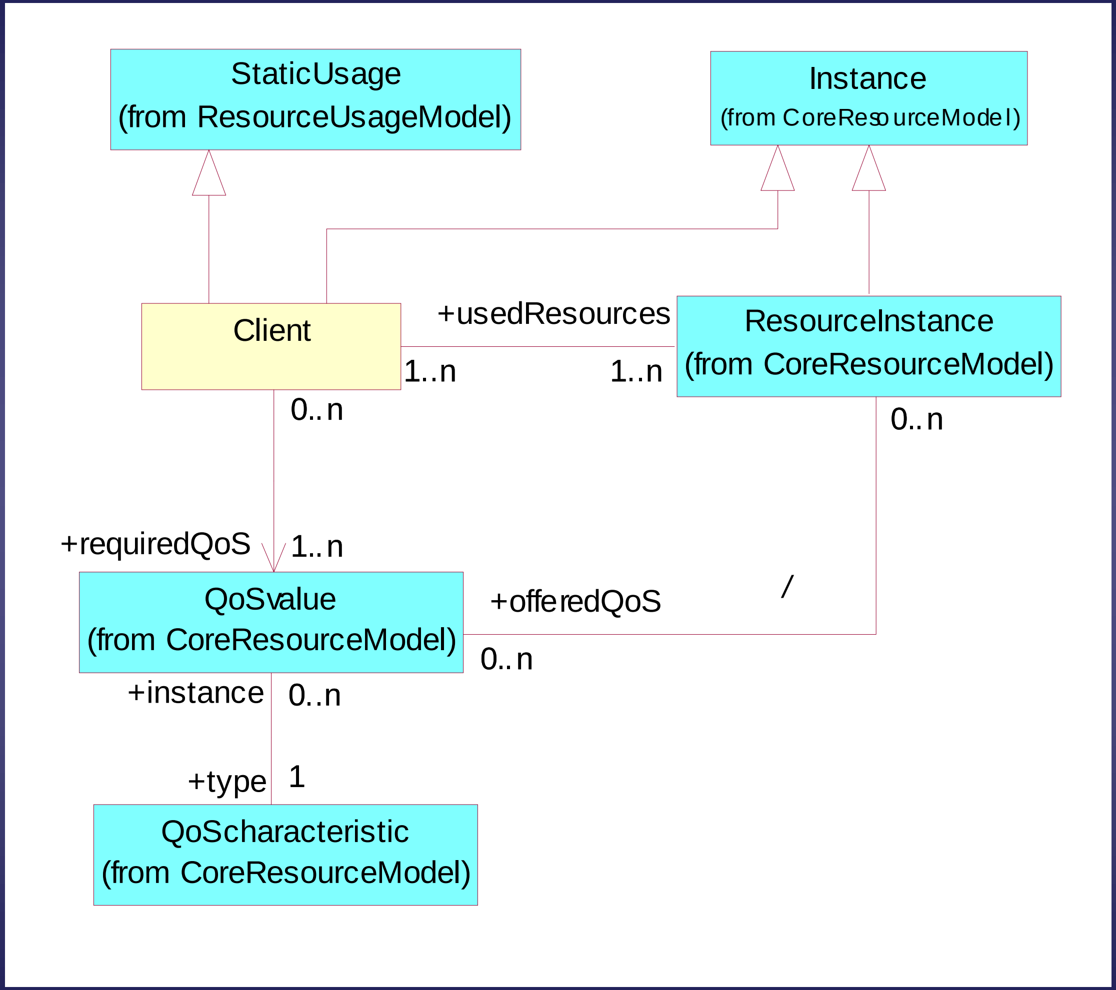
- Used in modeling dynamic scenarios



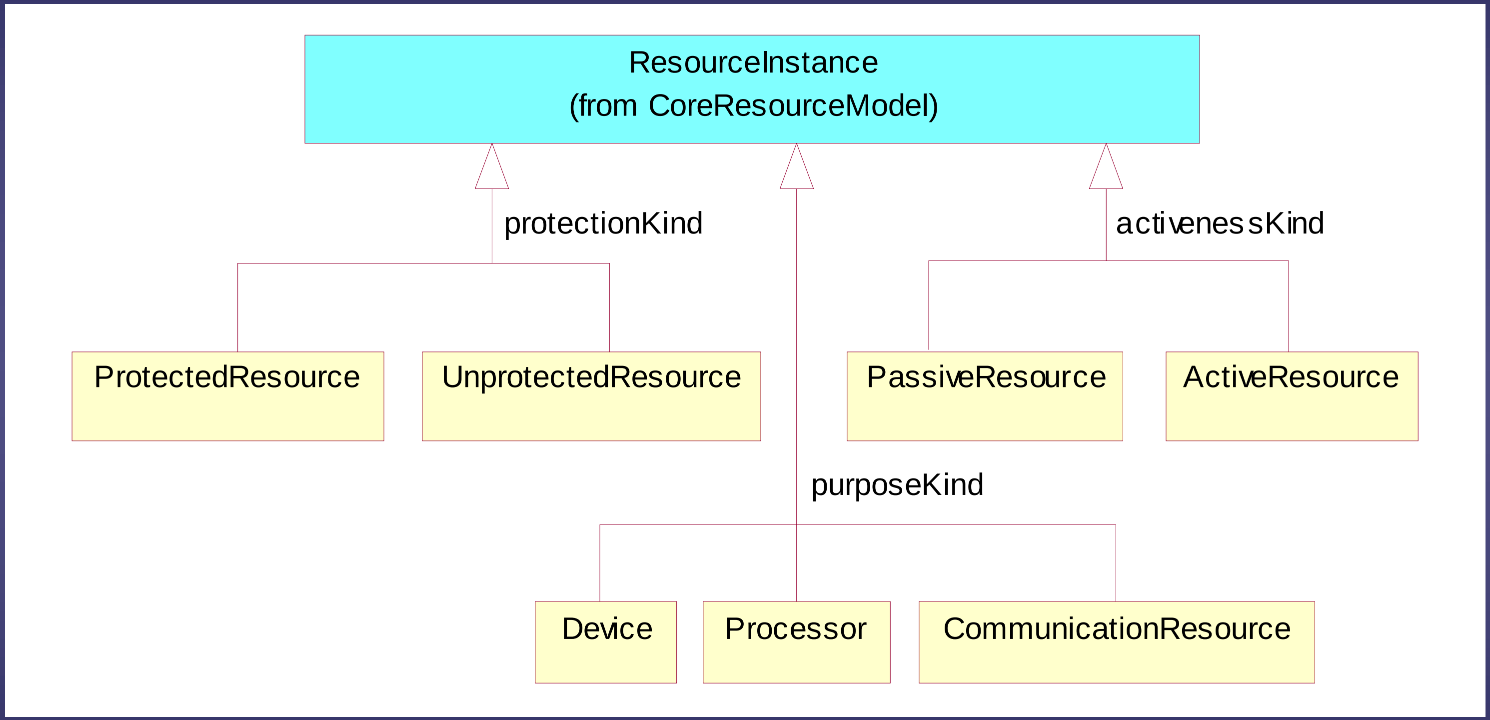
Dynamic Usage Model



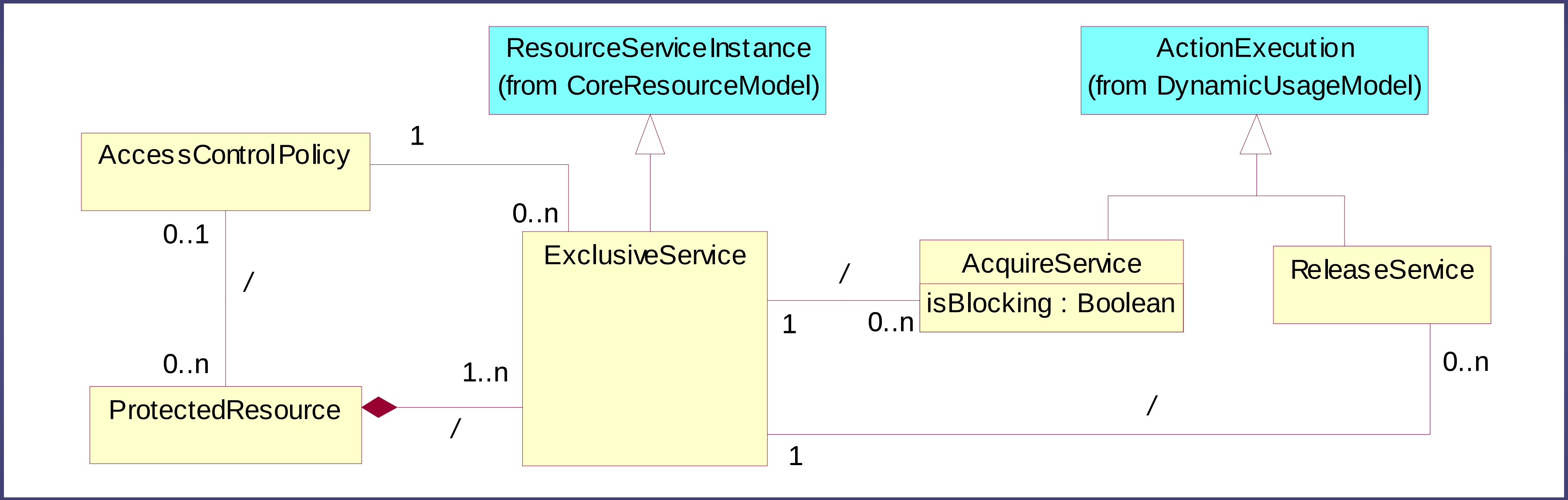
Static Usage Model



Resource Categorizations



Exclusive Use Resources and Actions



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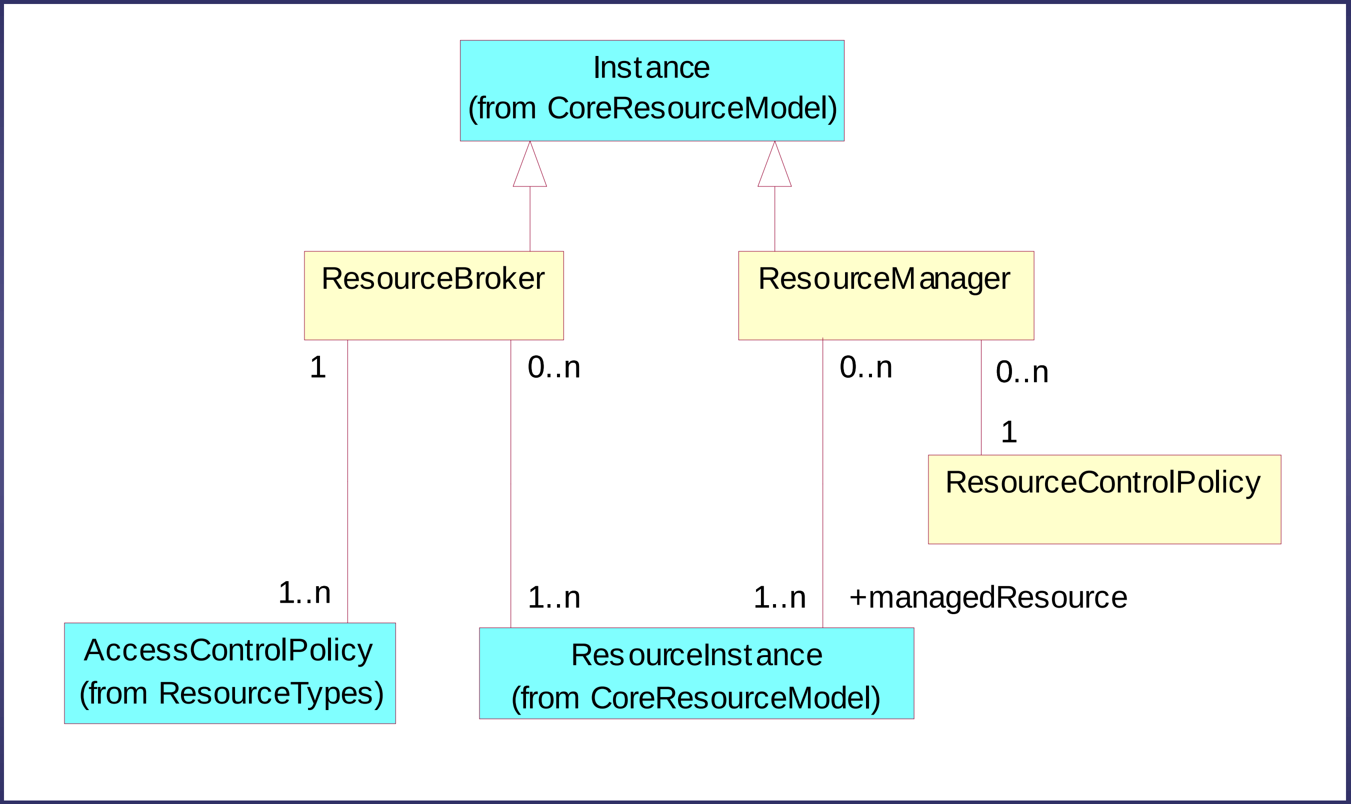
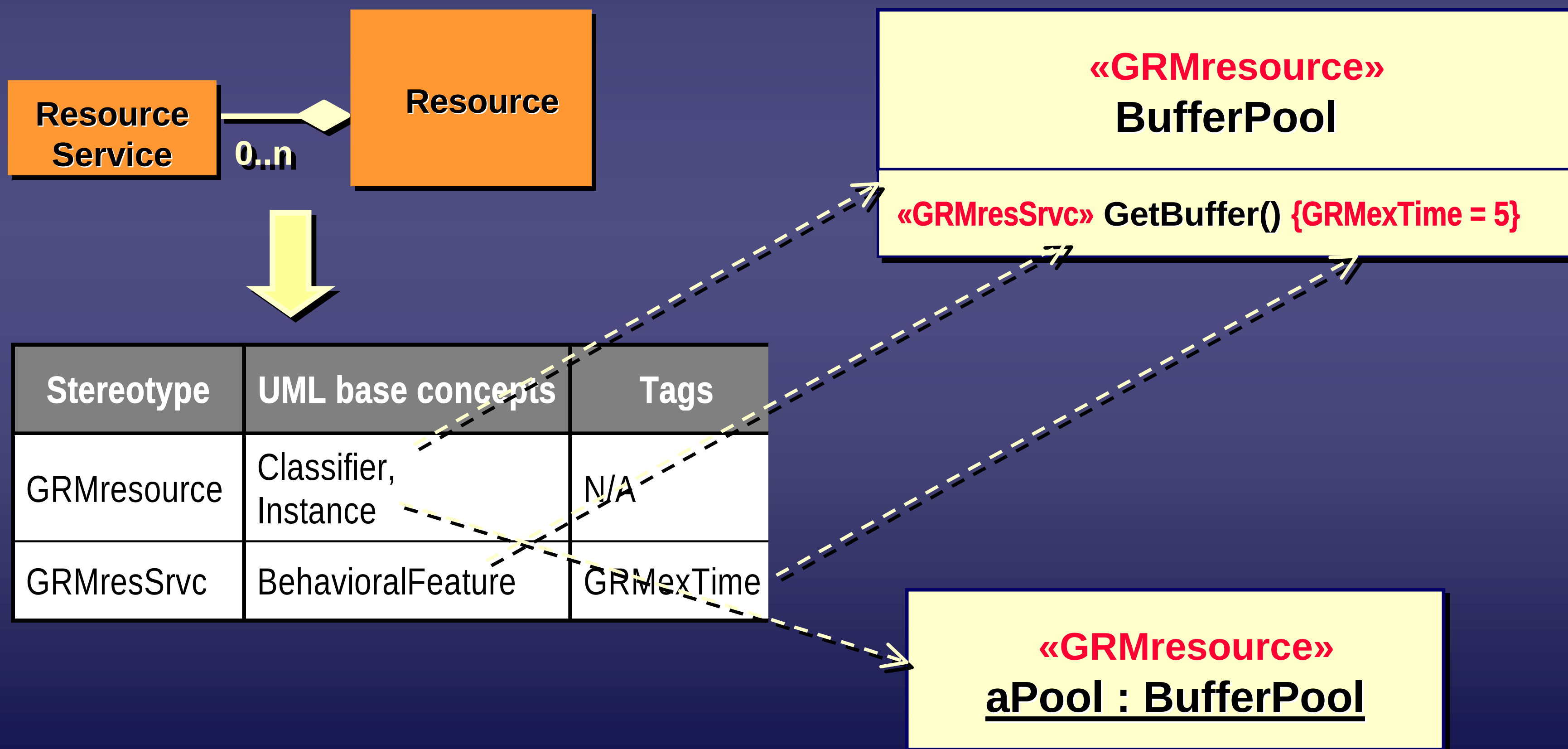
Resource Management Model



Mapping to UML Extensions

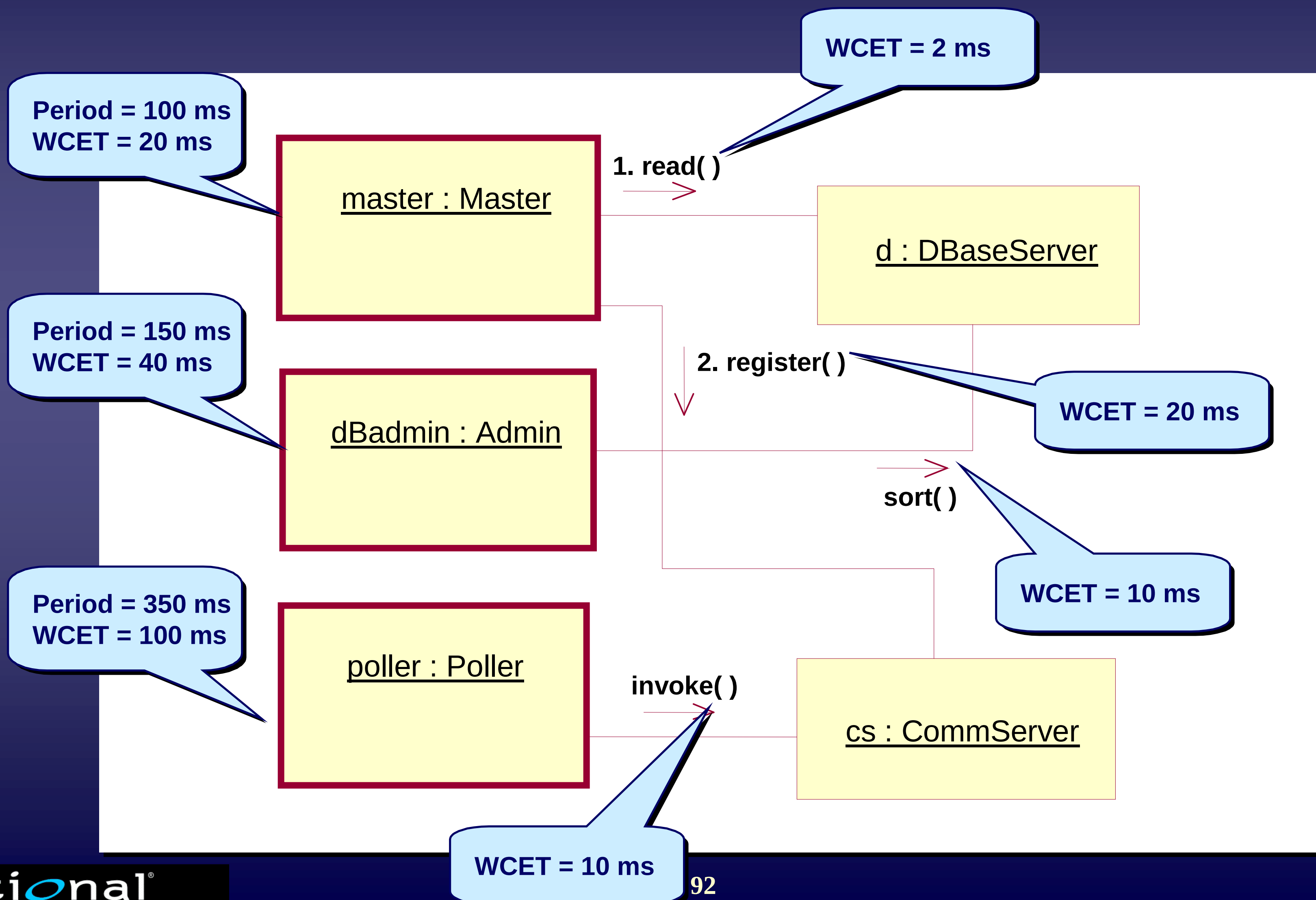
- Elements of the general resource model are represented as stereotypes (with tags) of base UML concepts:



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*

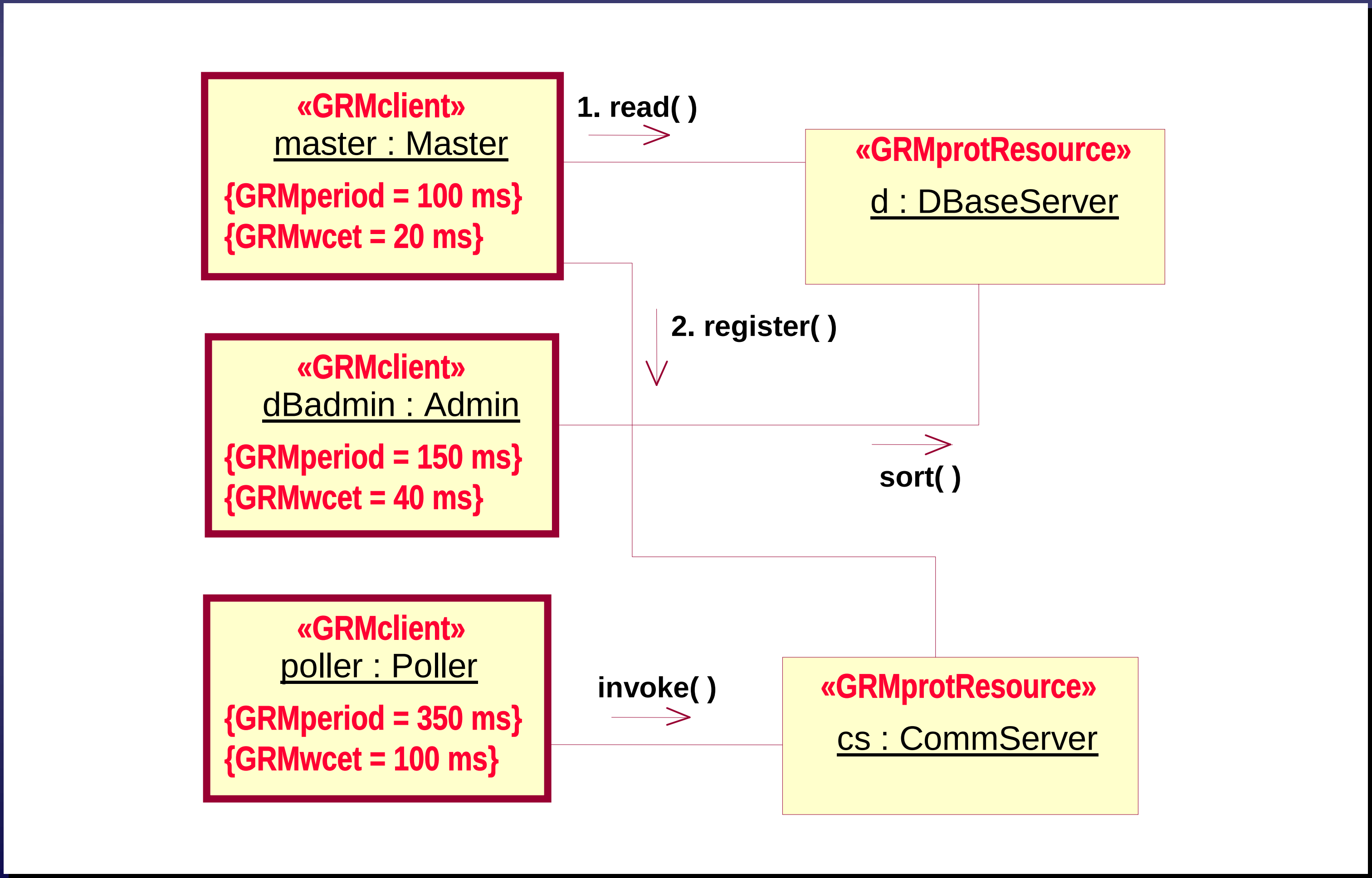
Stereotype	UML base concepts	Tags
GRMclient	Classifier, Instance	GRMperiod, GRMwcet
GRMprotResource	Classifier, Instance	N/A
GRMresService	BehavioralFeature	GRMwcet

Tag	Tag Type
GRMperiod	RTtimeString
GRMwcet	RTtimeString

* The stereotypes and tags have been simplified for this presentation

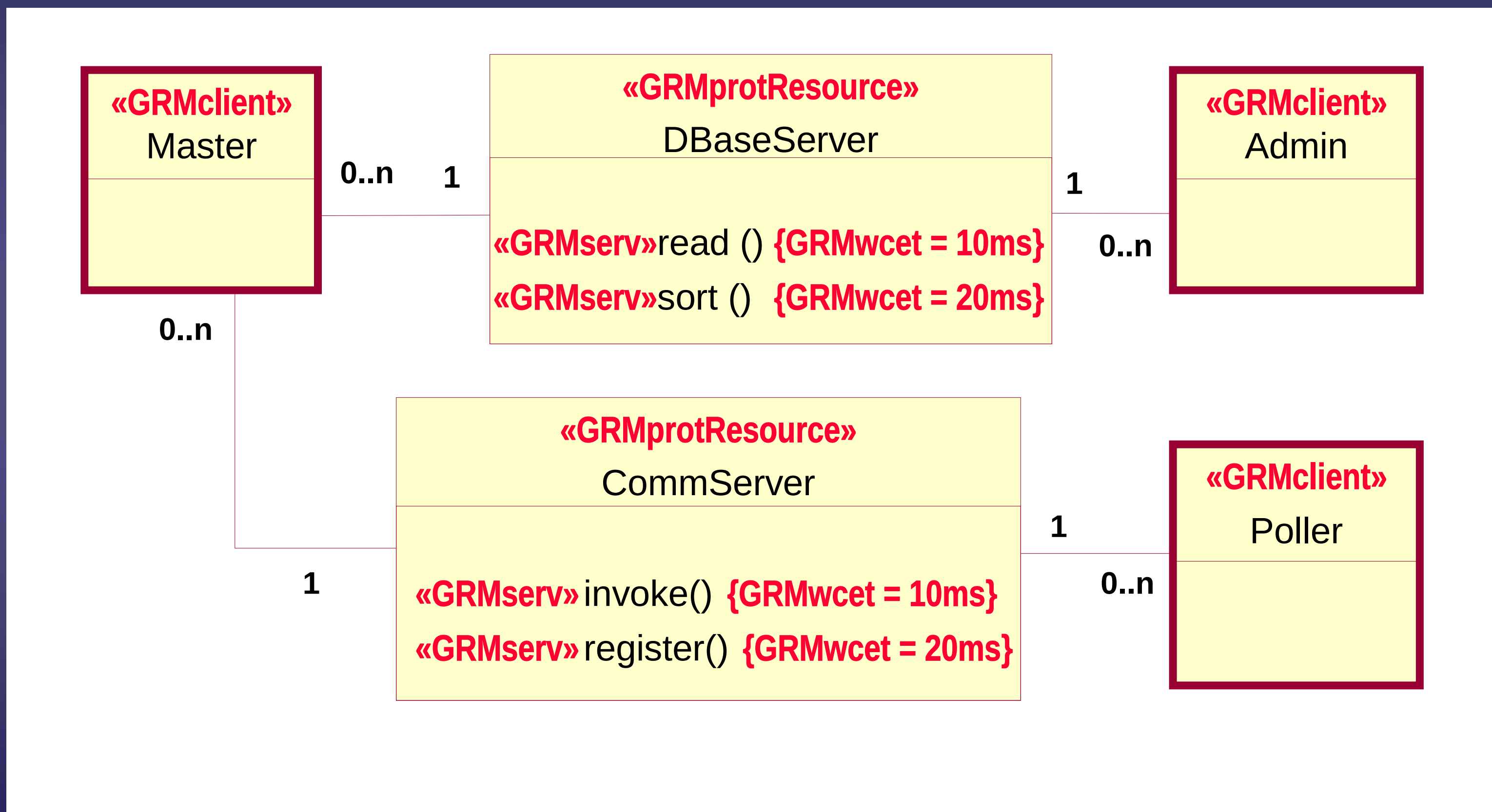
Example: QoS Annotations

- Using the standard stereotypes...

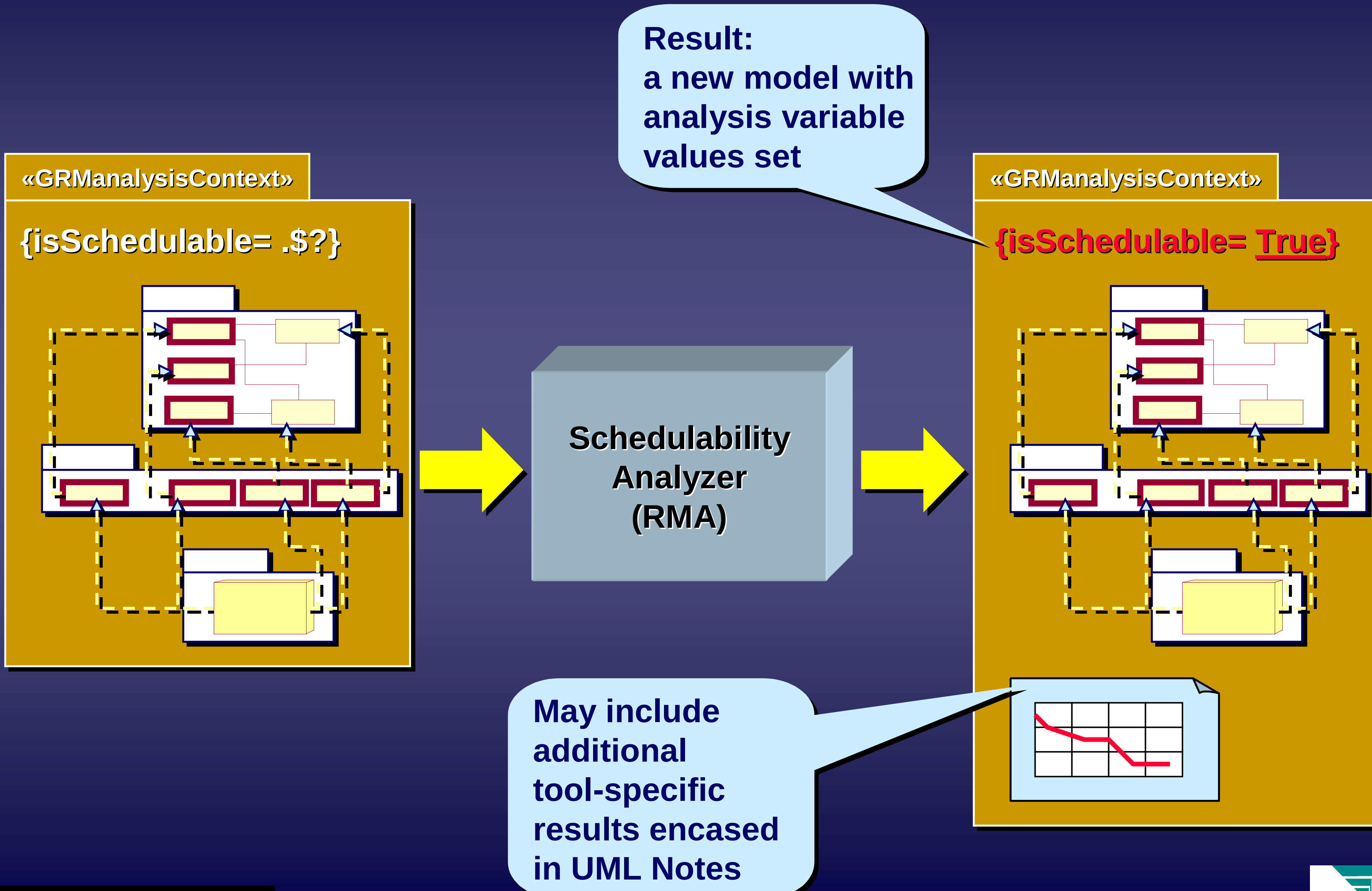


Example: Class Diagram

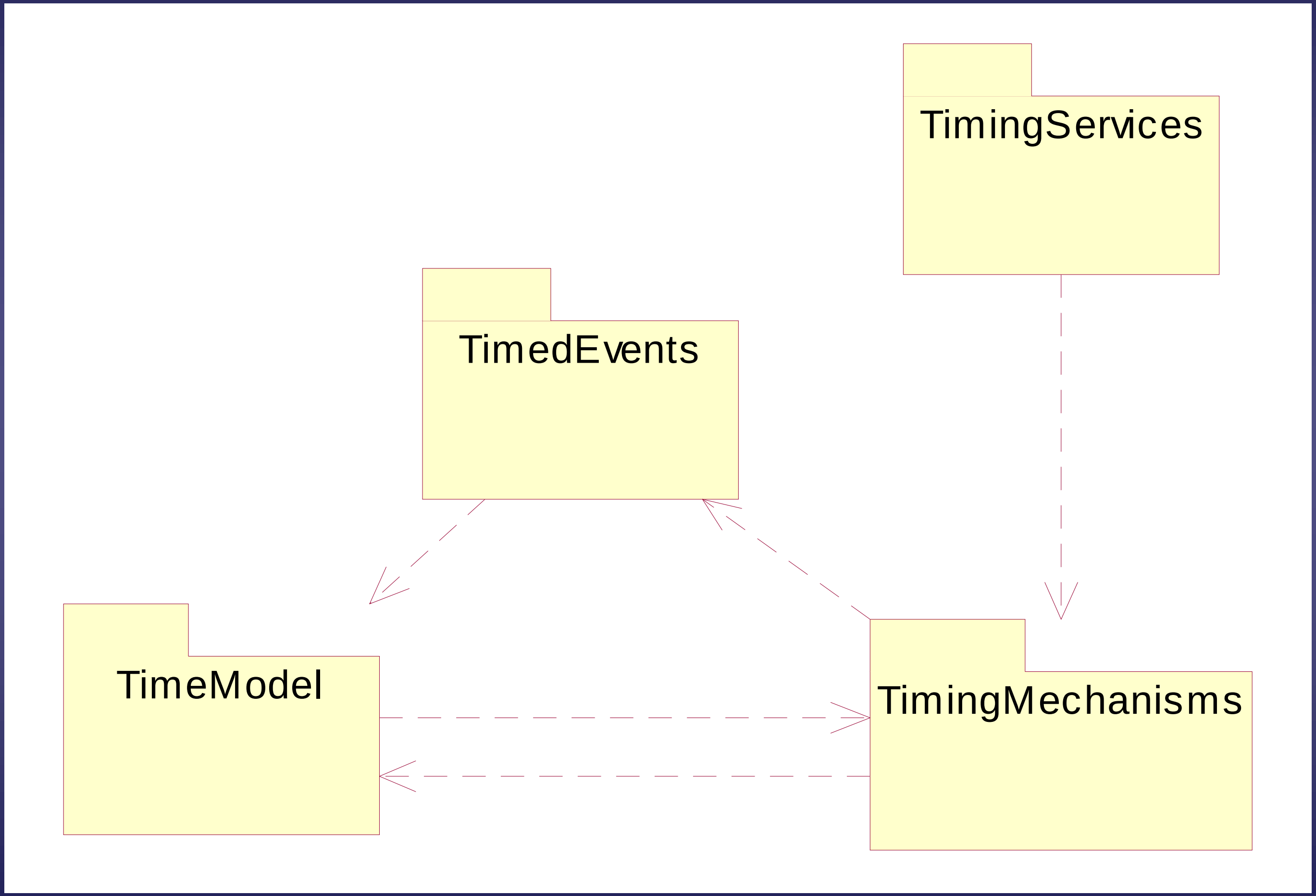
- QoS annotations can be added to classes as well



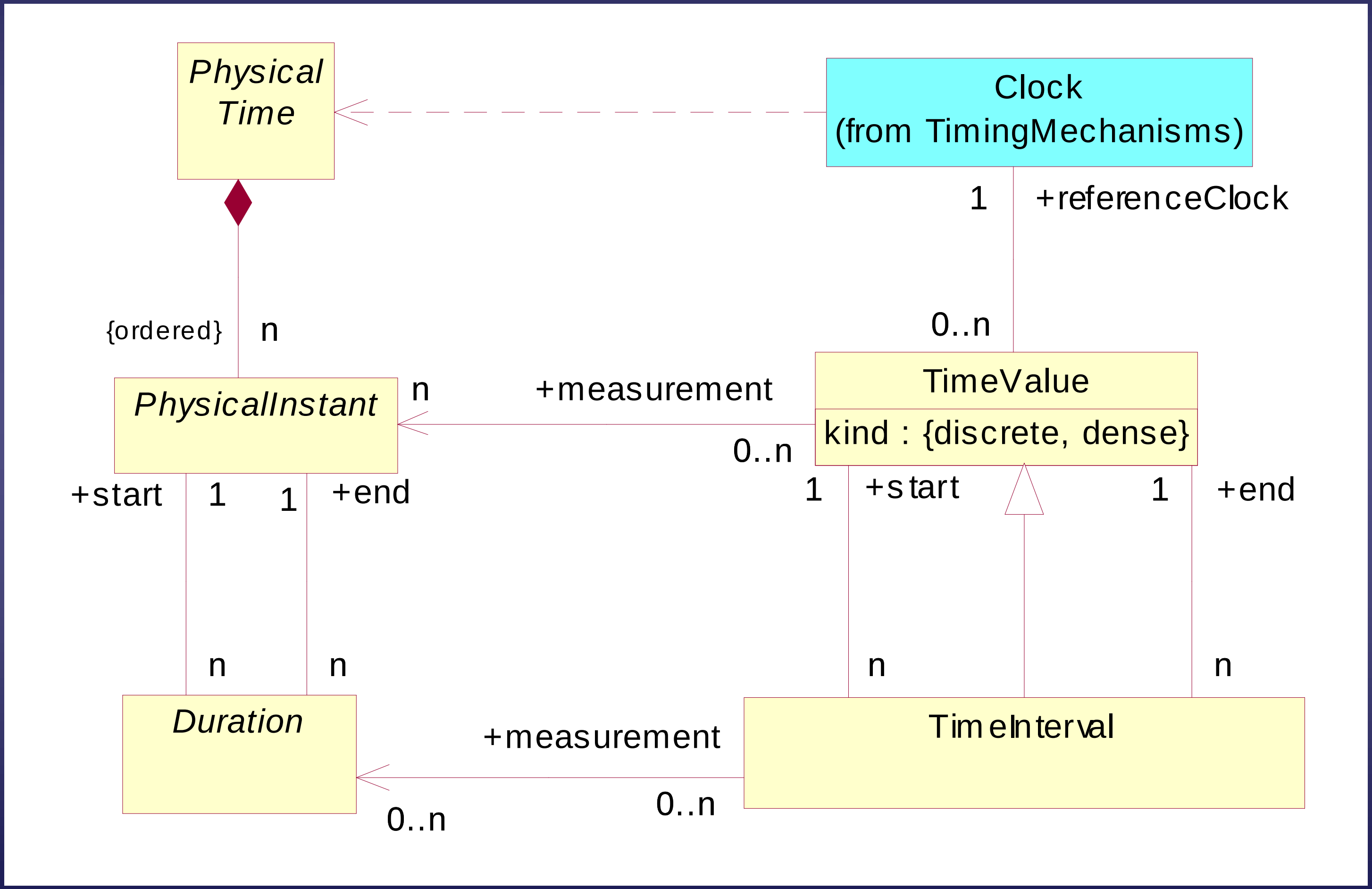
Example: Model Analysis



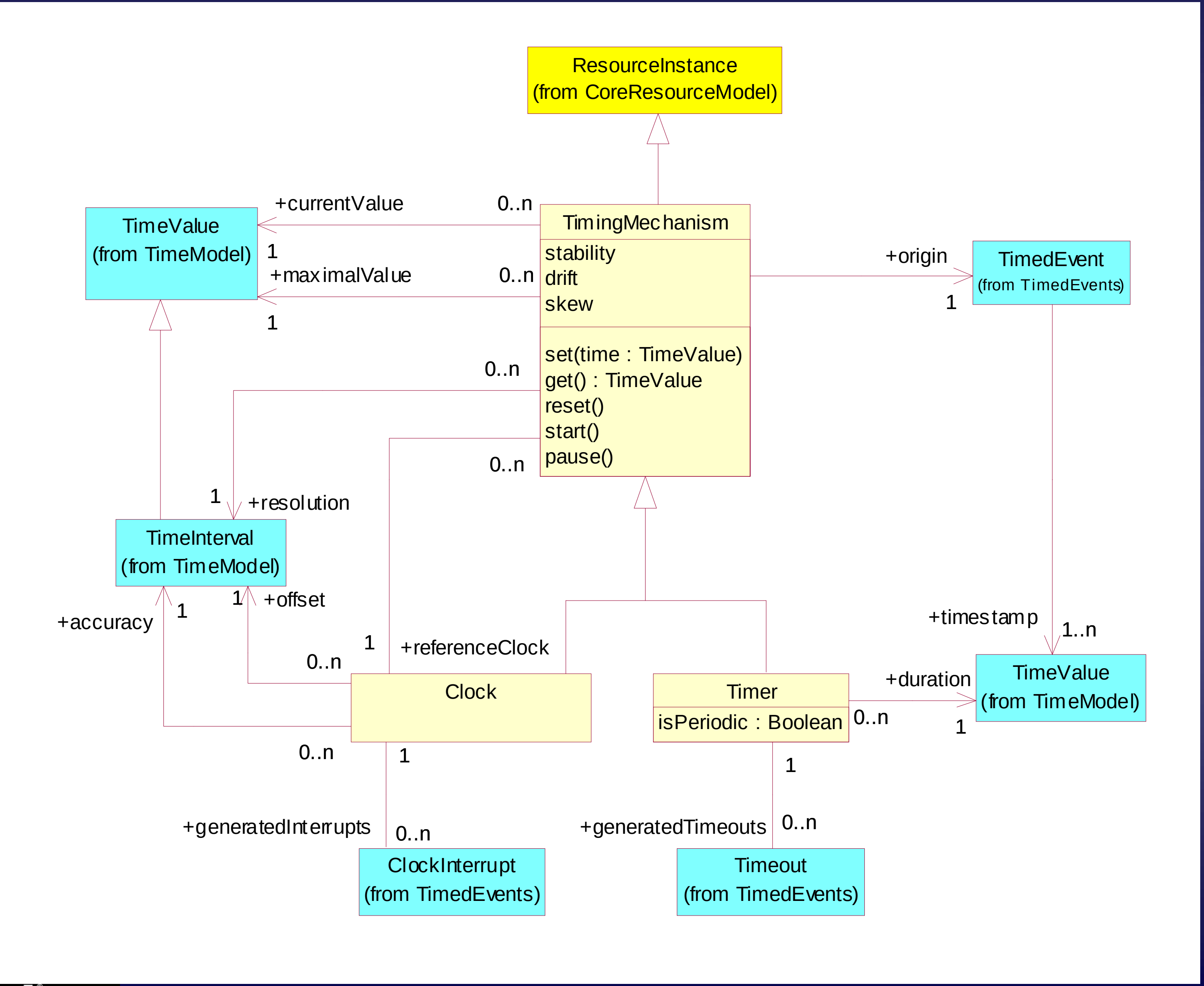
General Time Model



Physical and Measured Time



Timing Mechanisms Model



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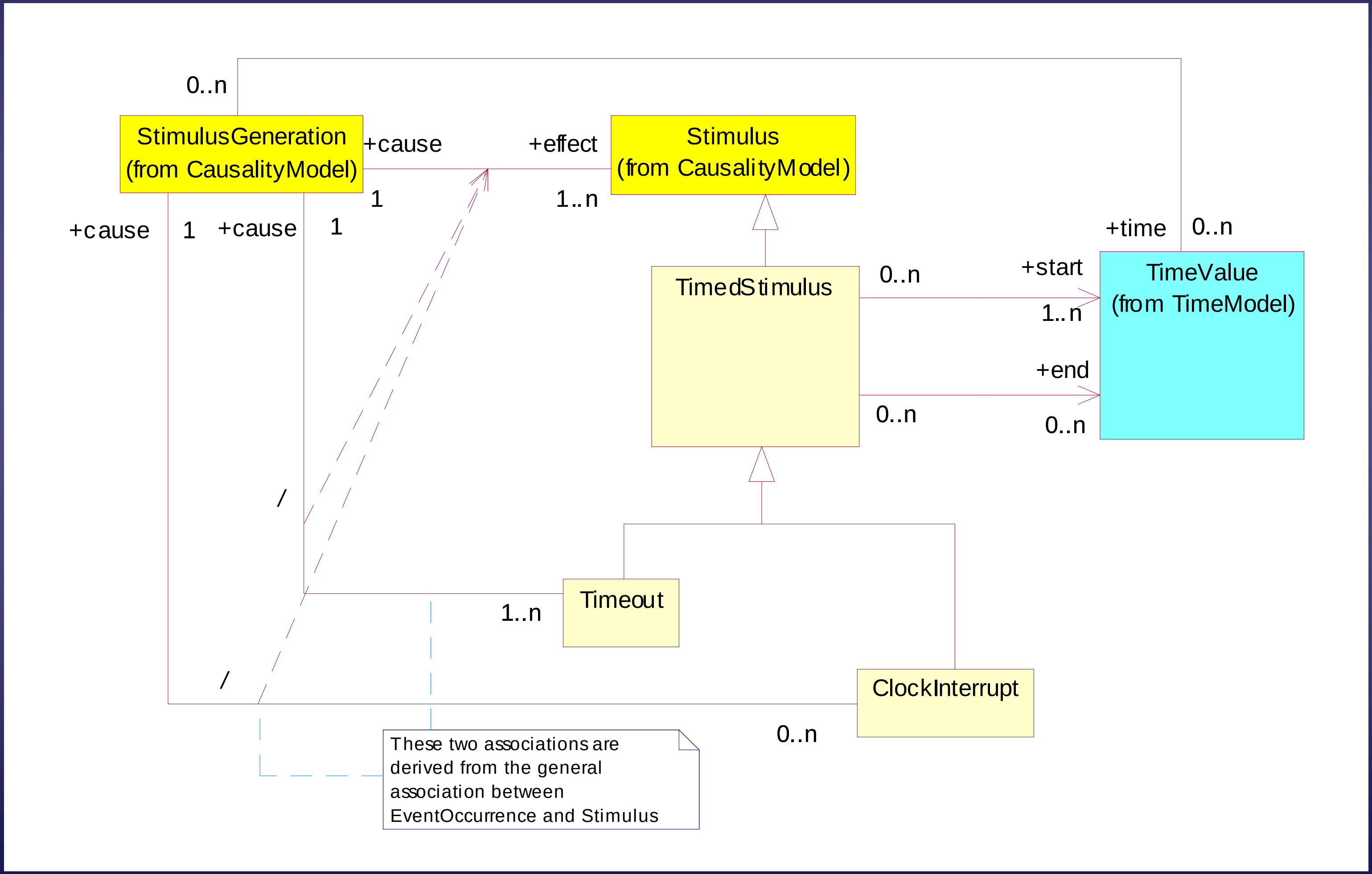
Example Timing Stereotype

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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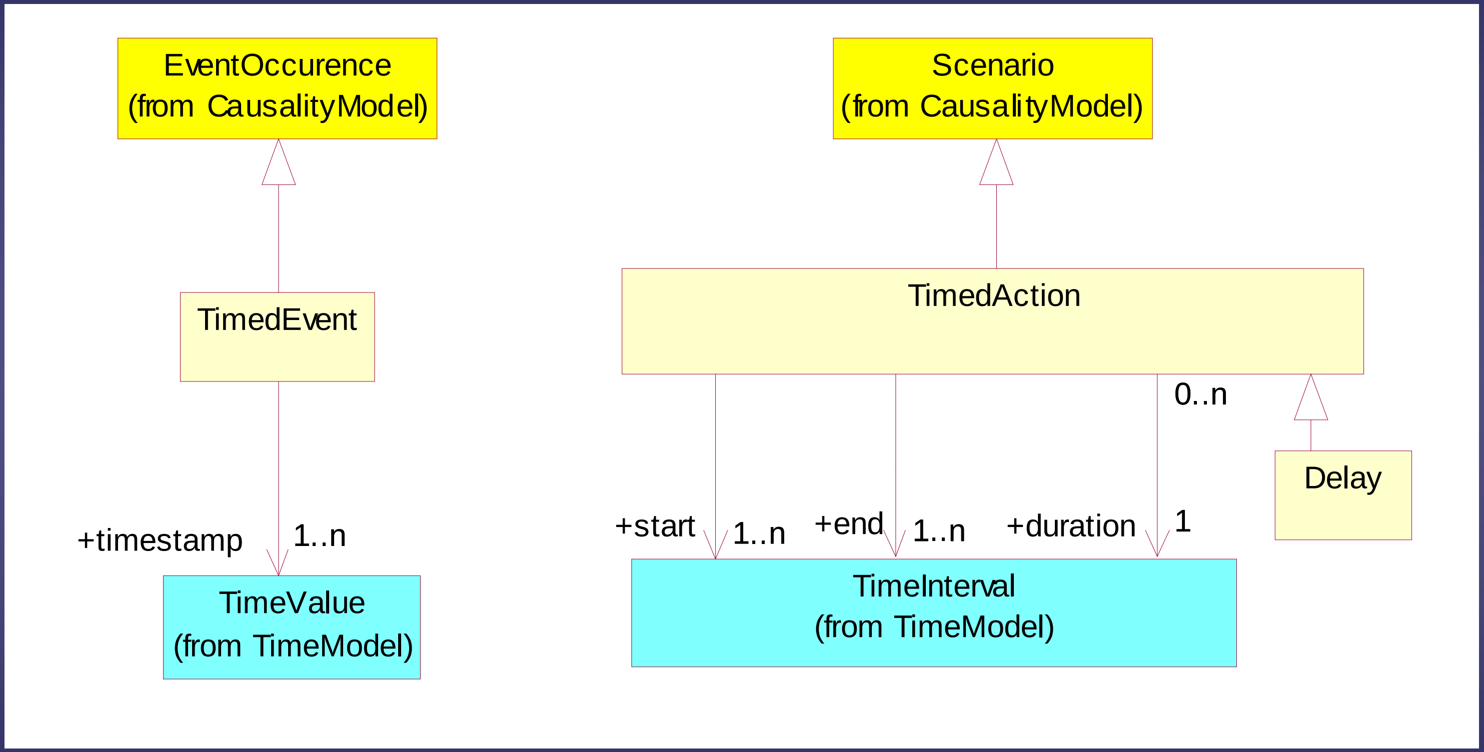
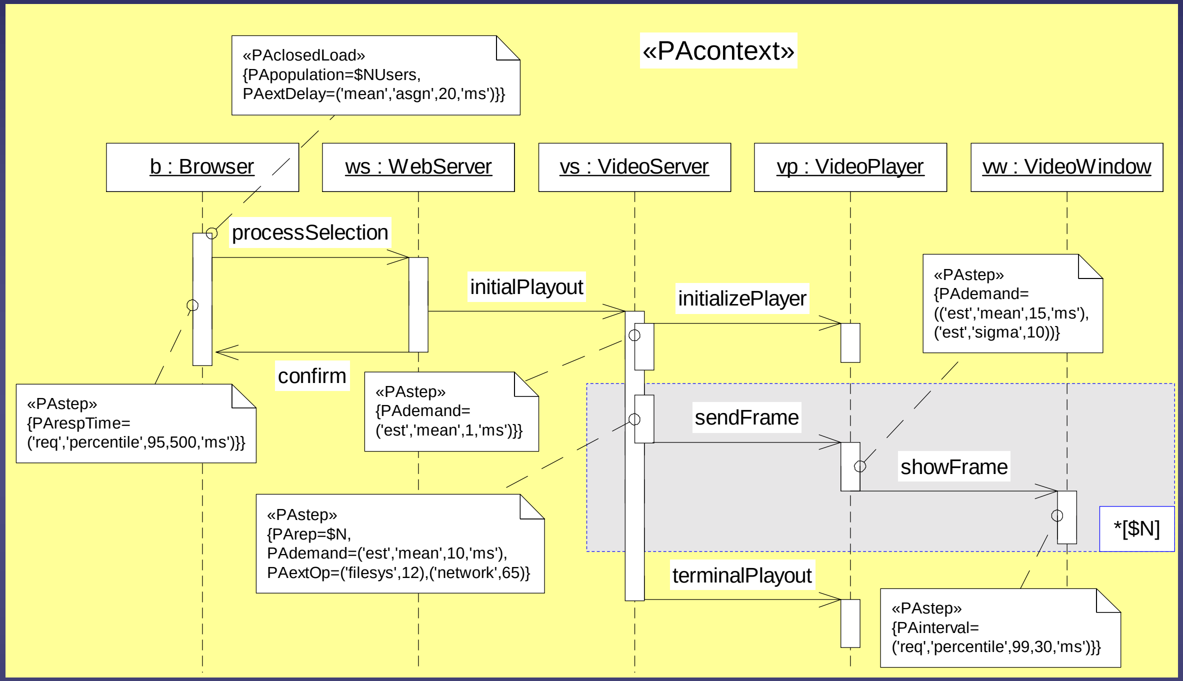
Timed Events and Timed Actions

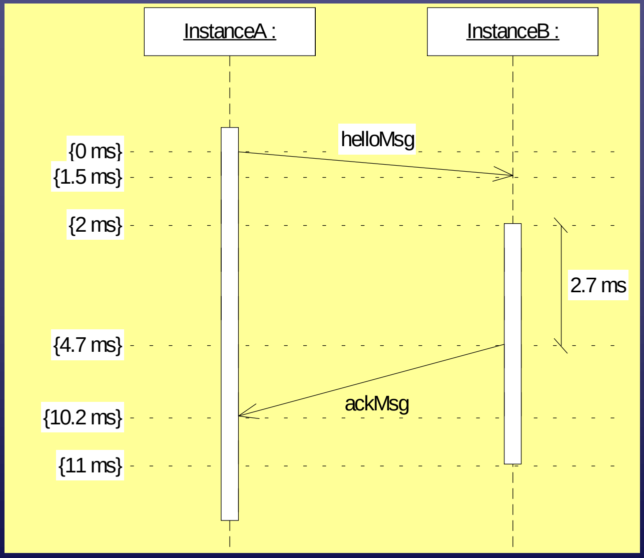


Time Annotations

- 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)

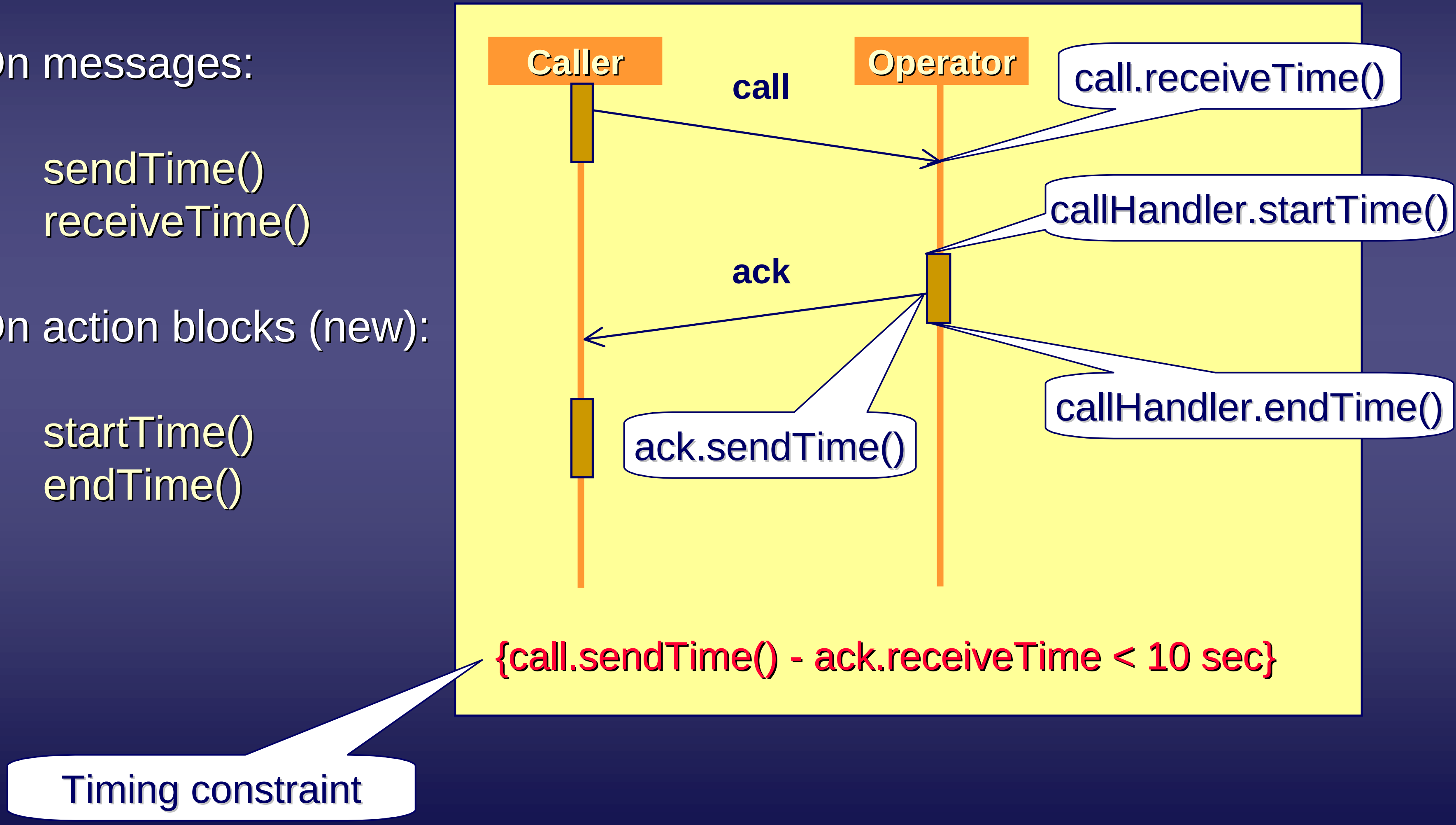
Notation: Timing Marks and Constraints

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

    sendTime()
    receiveTime()

  - On action blocks (new):

    startTime()
    endTime()



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)

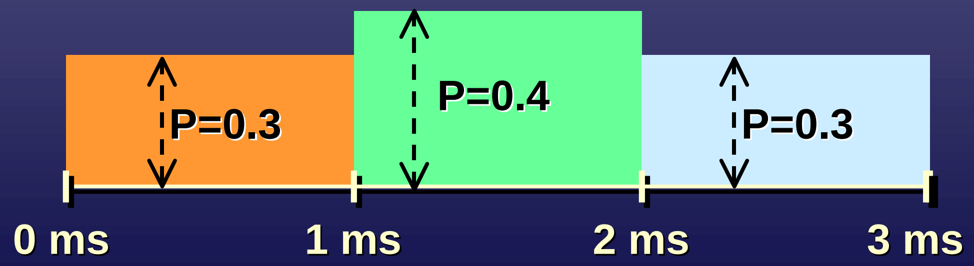
Stereotype	Applies To	Tags	Description
«RTnewClock	Operation	RTstart [0..1] RTend [0..1] RTduration [0..1]	An operation that creates a new clock mechanism
«RTnewTimer»	Operation	RTtimerPar [0..1]	An operation that creates a new timer
«RTpause»	Operation		A pause operation on a timing mechanism
«RTreset»	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

Specifying Time Values

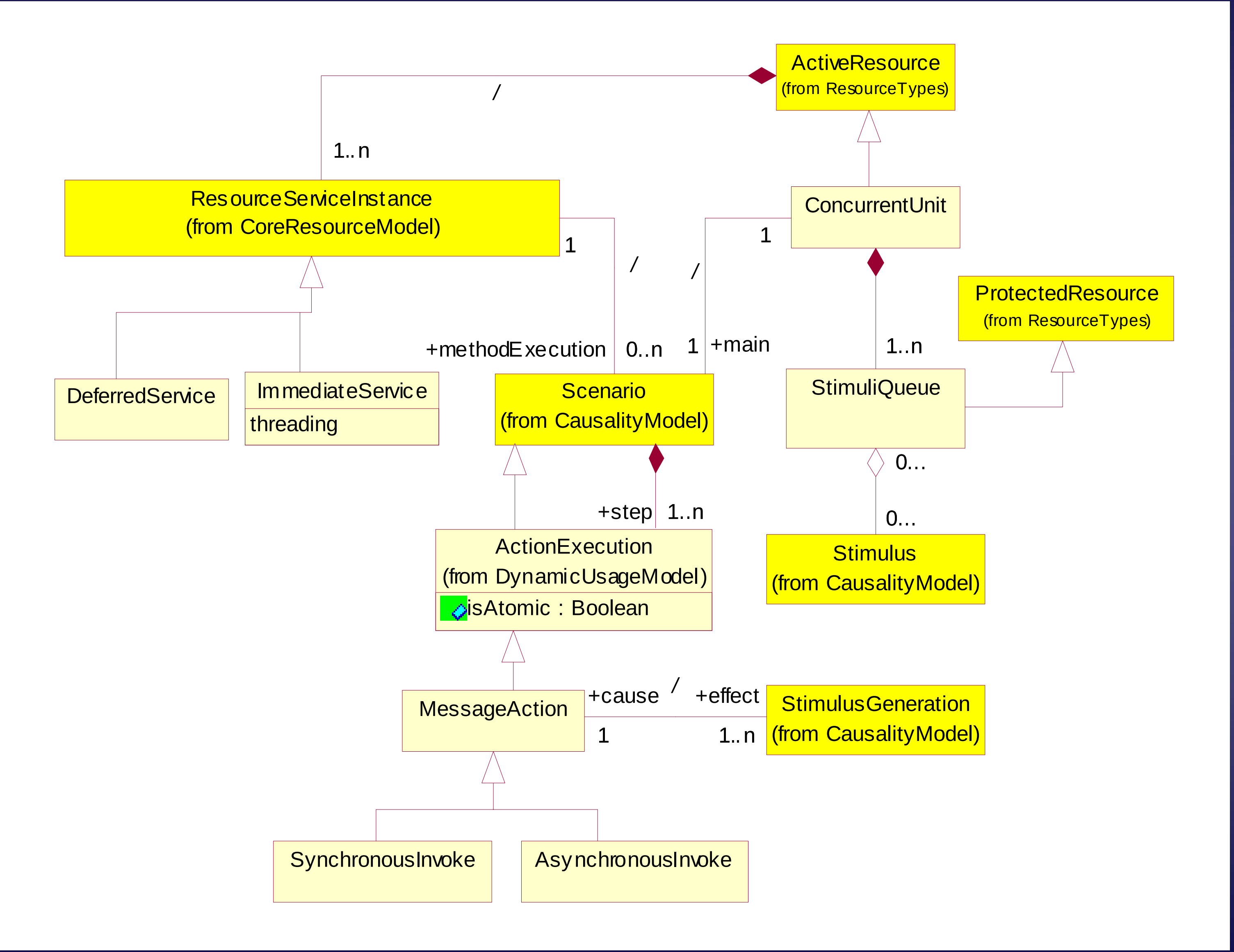
- Time values can be represented by a special stereotype of Value («RTtimeValue») in different formats; e.g.
  - 12:04 (time of day)
  - 5.3, ‘ms’ (time interval)
  - 2000/10/27 (date)
  - Wed (day of week)
  - $param, ‘ms’ (parameterized value)
  - ‘poisson’, 5.4, ‘sec’ (time value with a Poisson distribution)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



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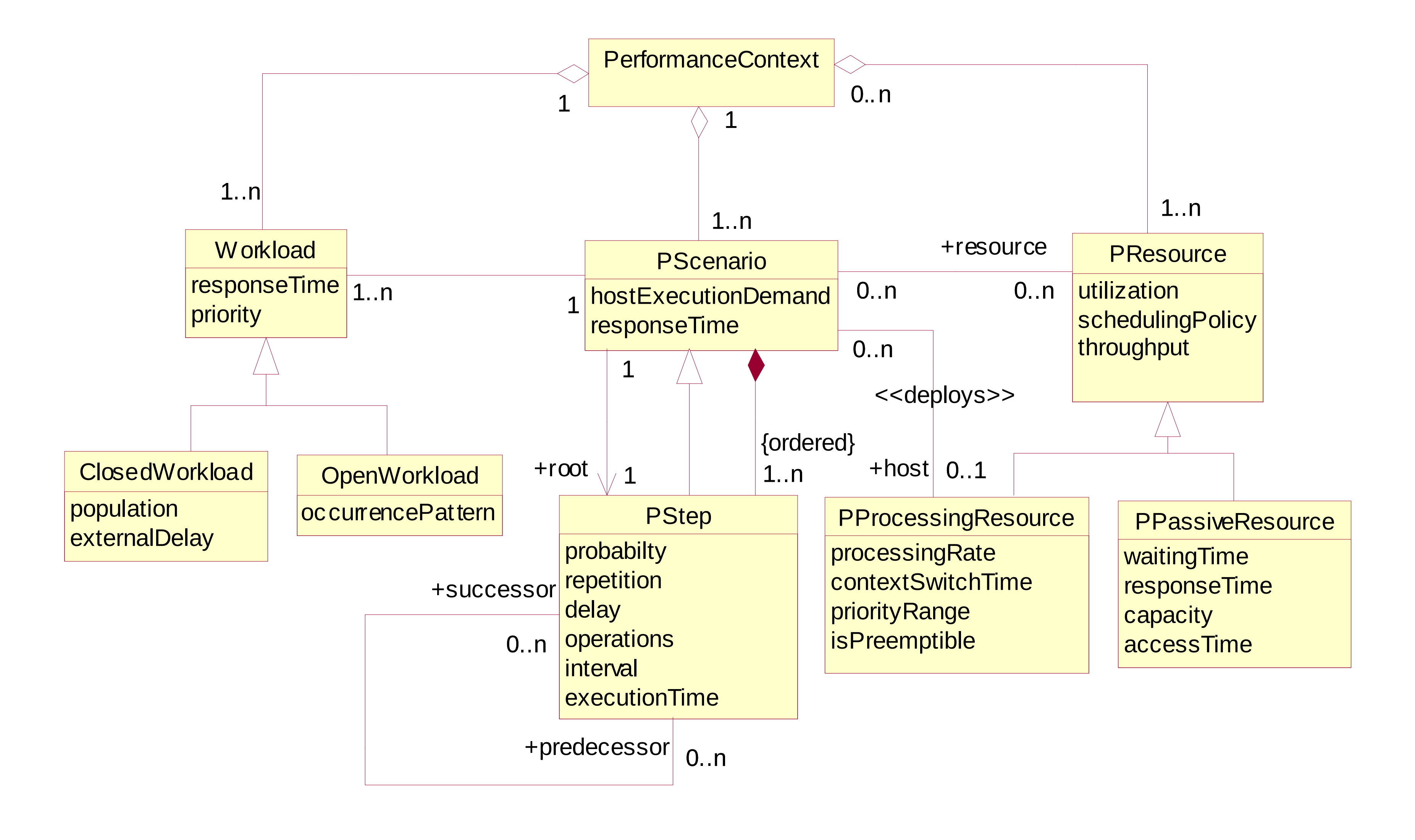
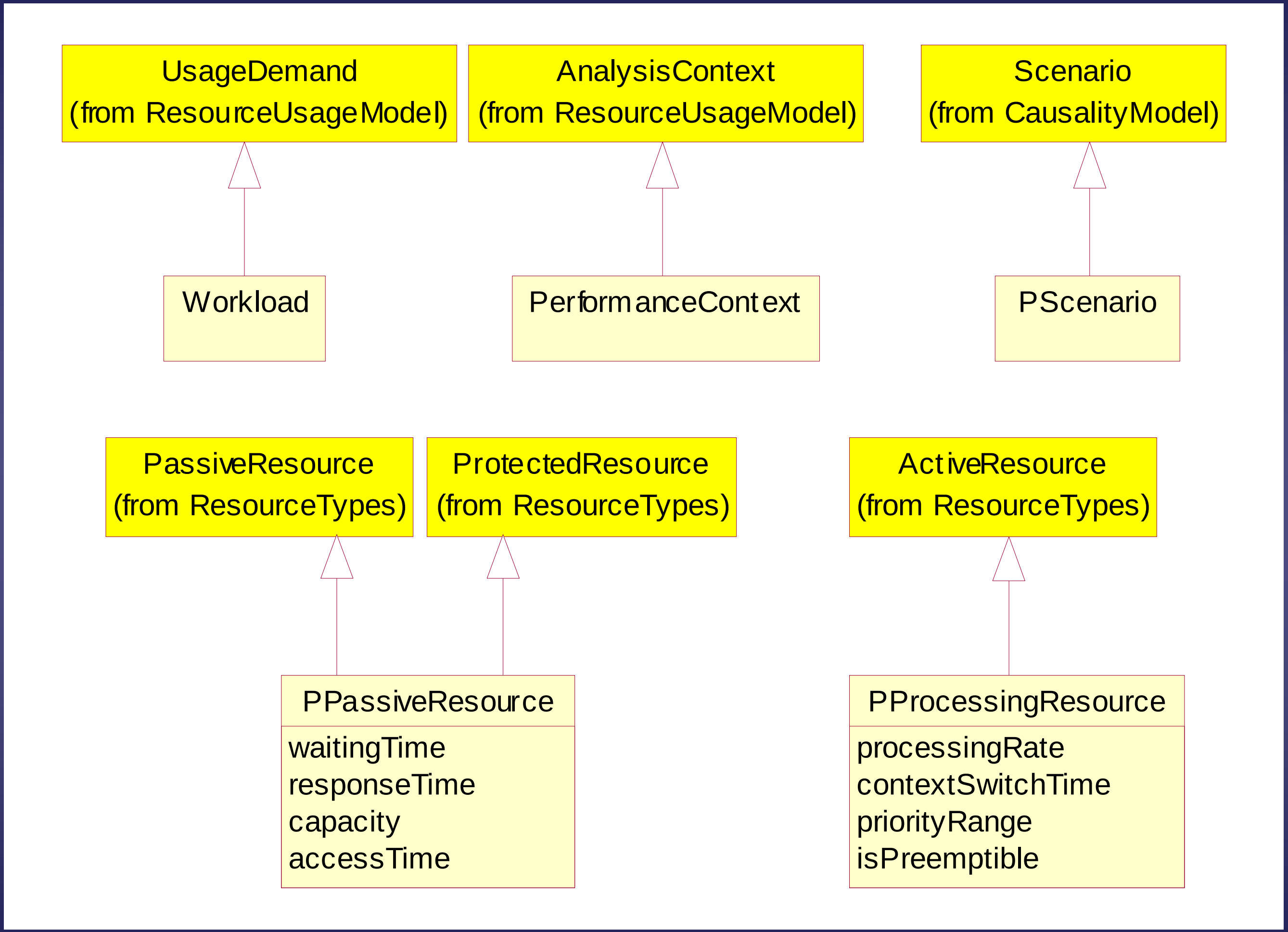
Defined Stereotypes

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

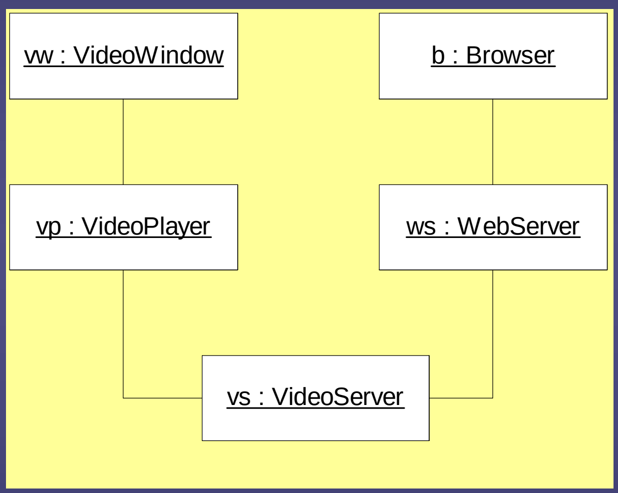


Relationship to General Resource Model

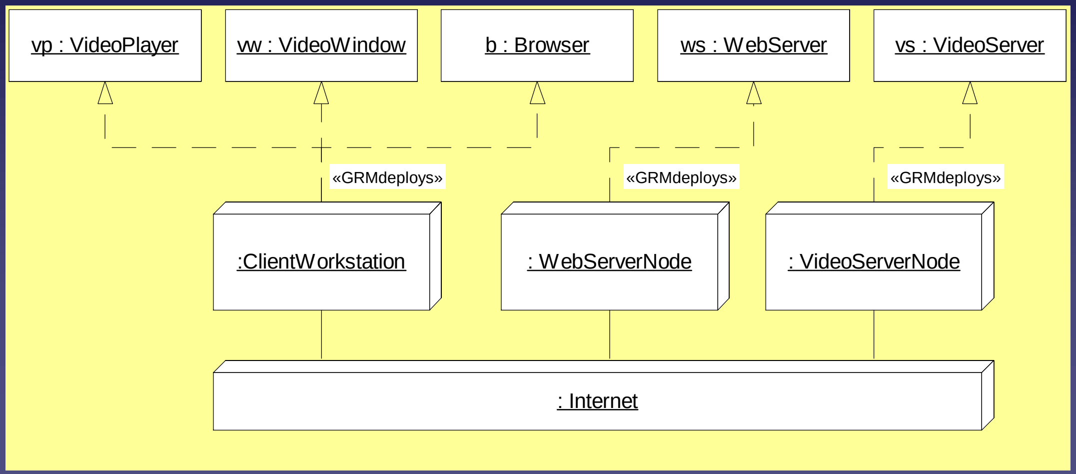


Example: Web Video Application

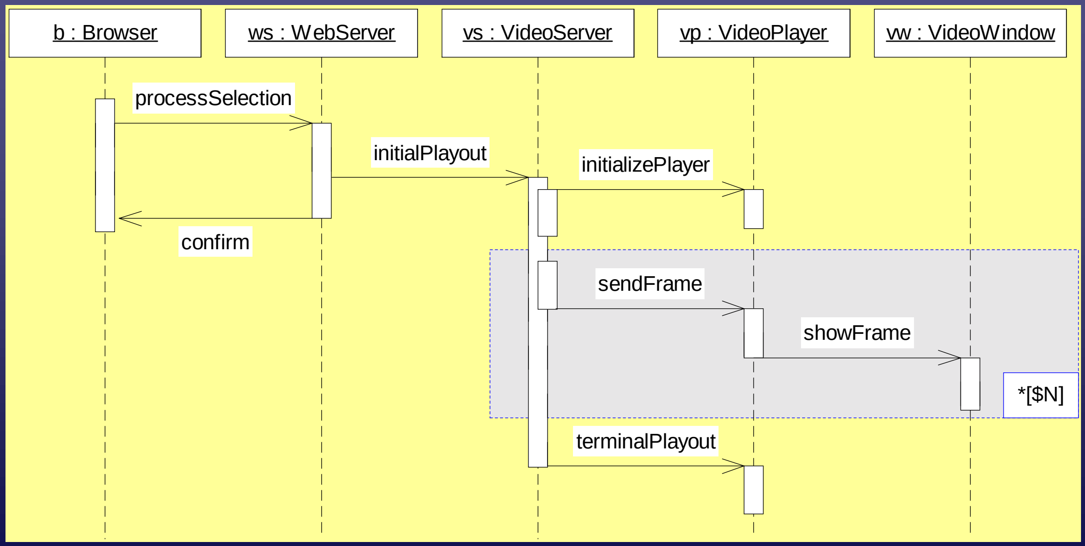
Logical Instance Model



Engineering Instance Model



Usage Scenario



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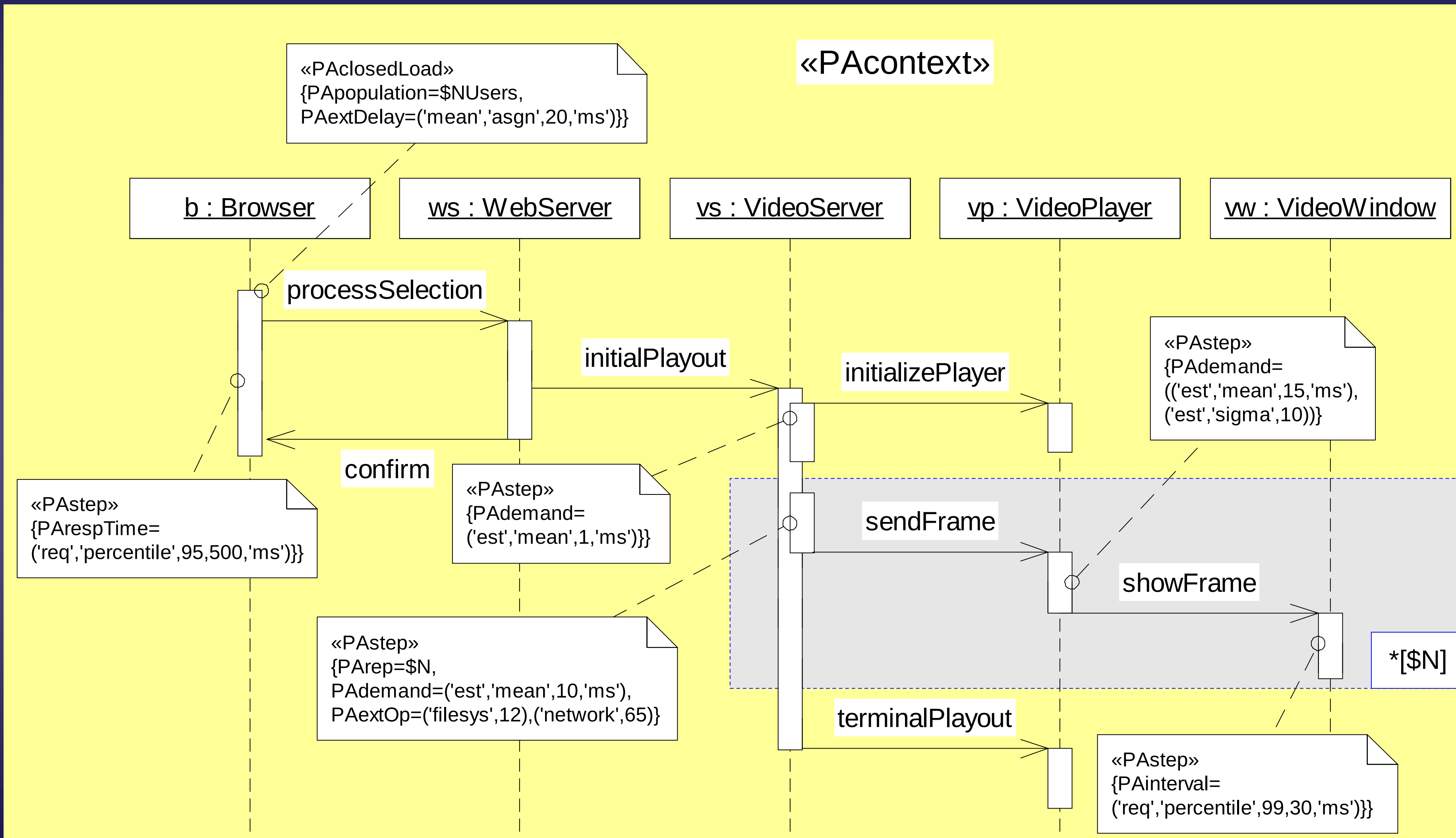
Example: Performance Requirements

- 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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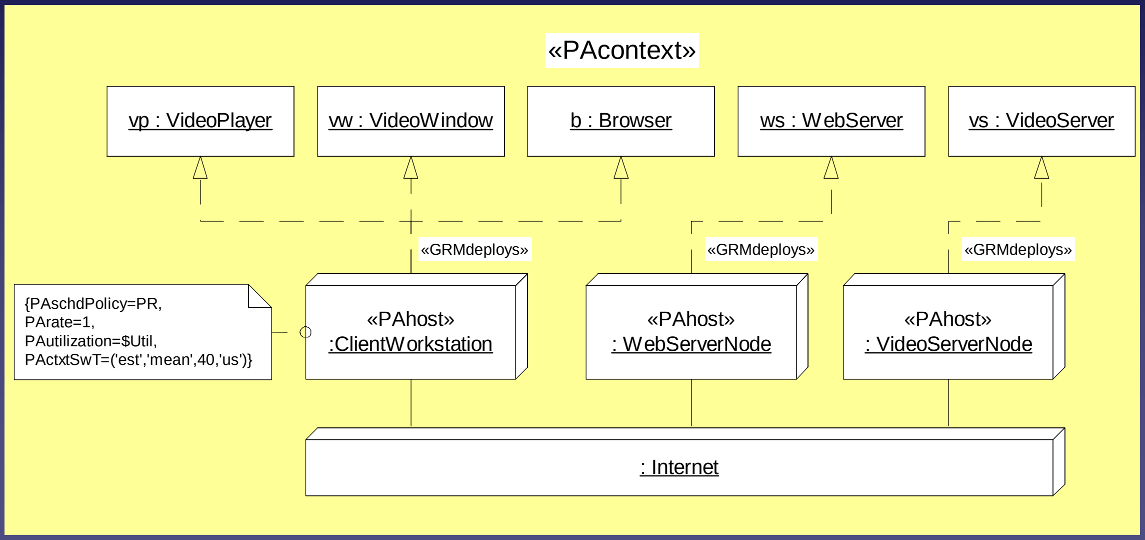
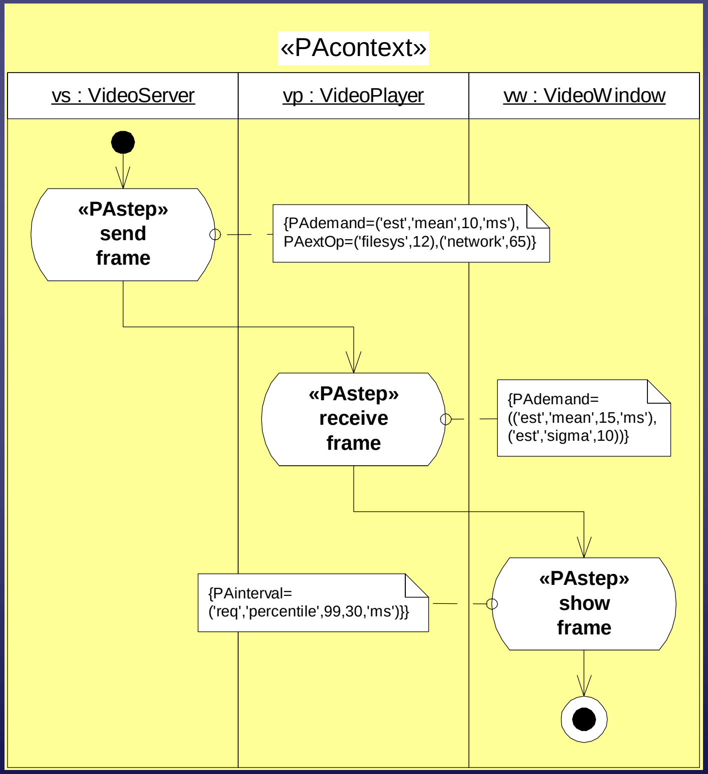
Example: More Annotations





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)

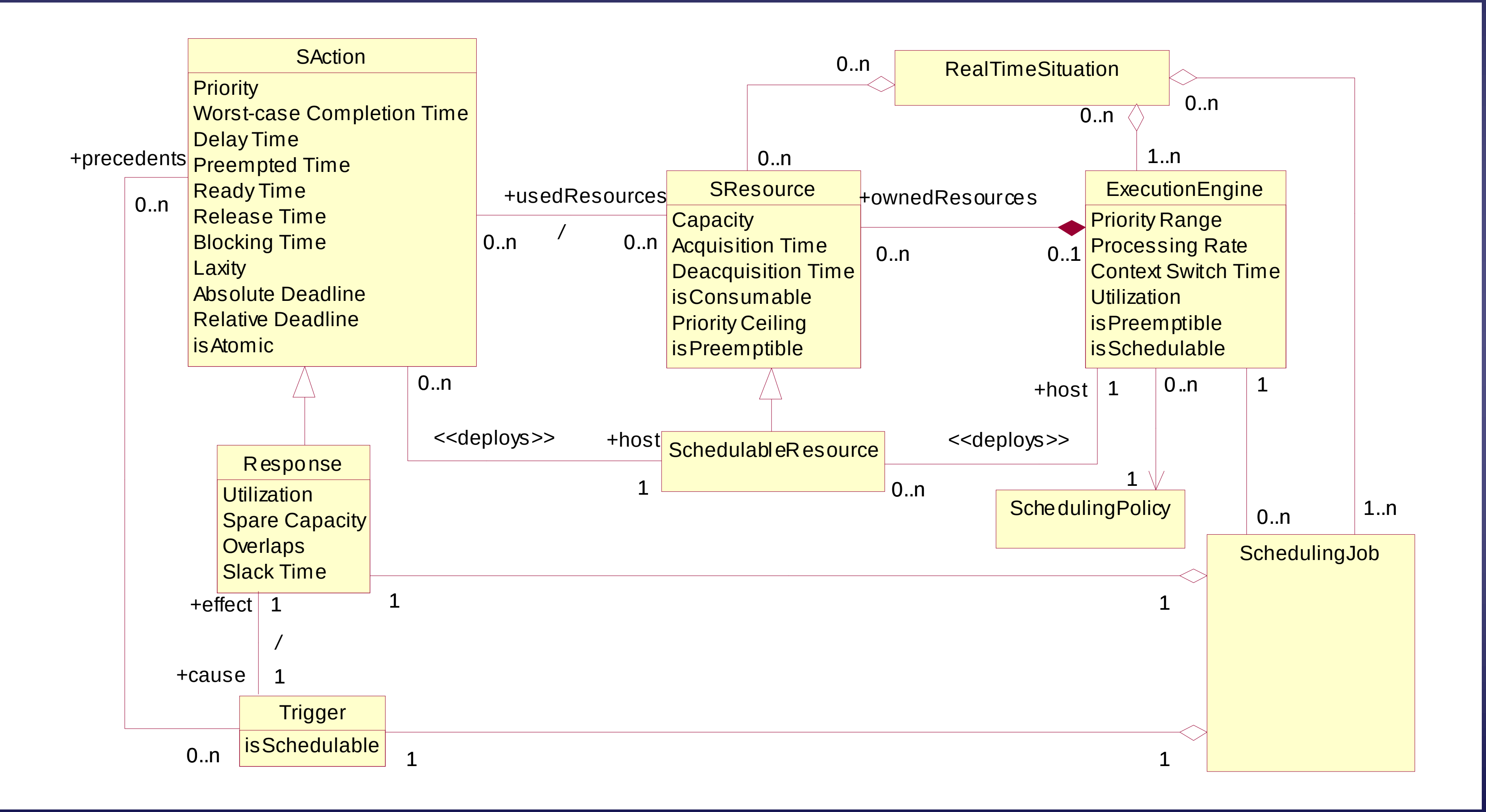
Stereotype	Applies To	Tags	Description
«PAresource»	Classifier, Node, ClassifierRole, Instance, Partition	PAutilization [0..*] PAschdPolicy [0..1] PAcapacity [0..1] PAmaxTime [0..1] PArespTime [0..1] PAwaitTime [0..1] PAthroughput [0..1]	A passive resource
«PAstep»	Message, ActionState, Stimulus, SubactivityState	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



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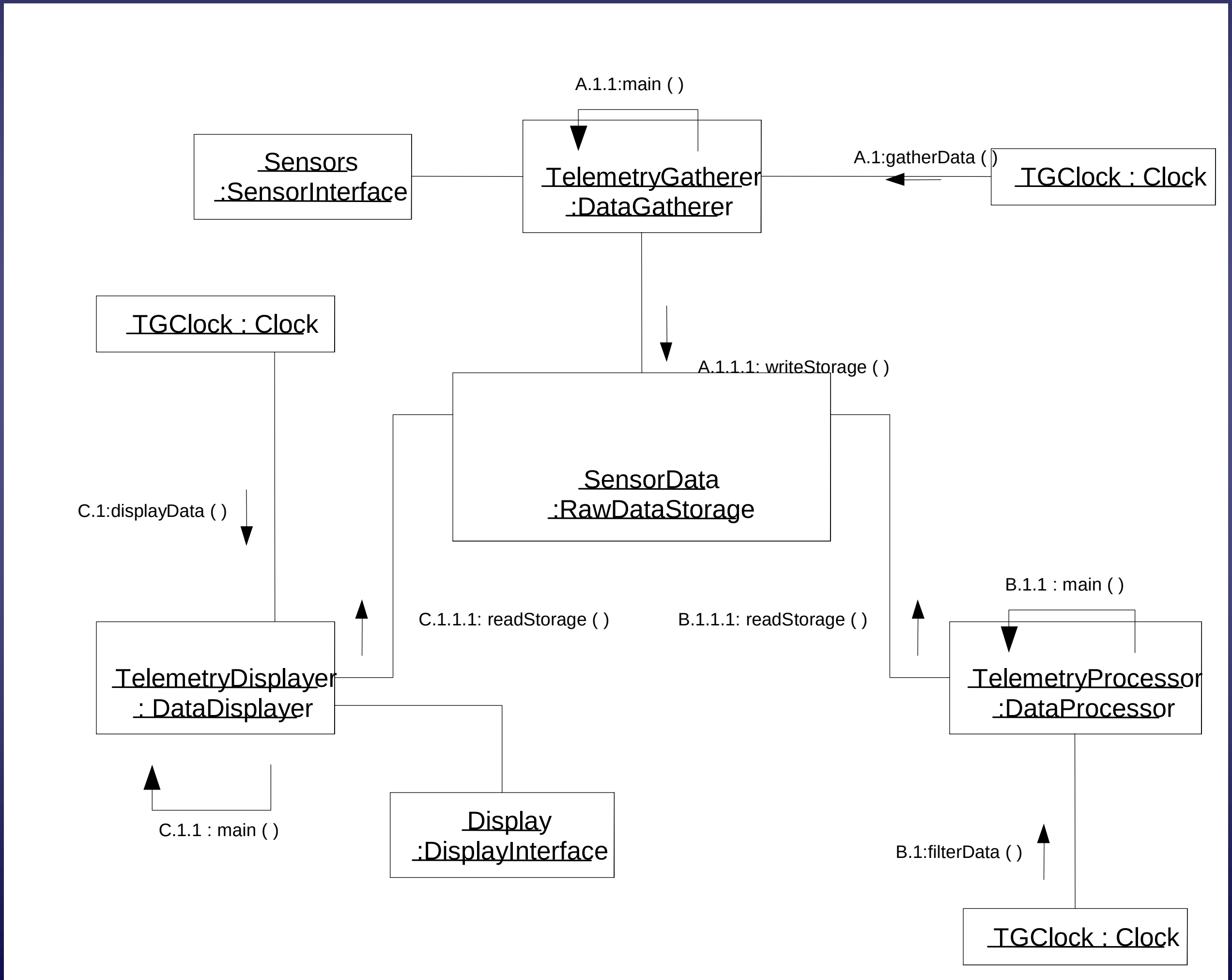
Policies Supported

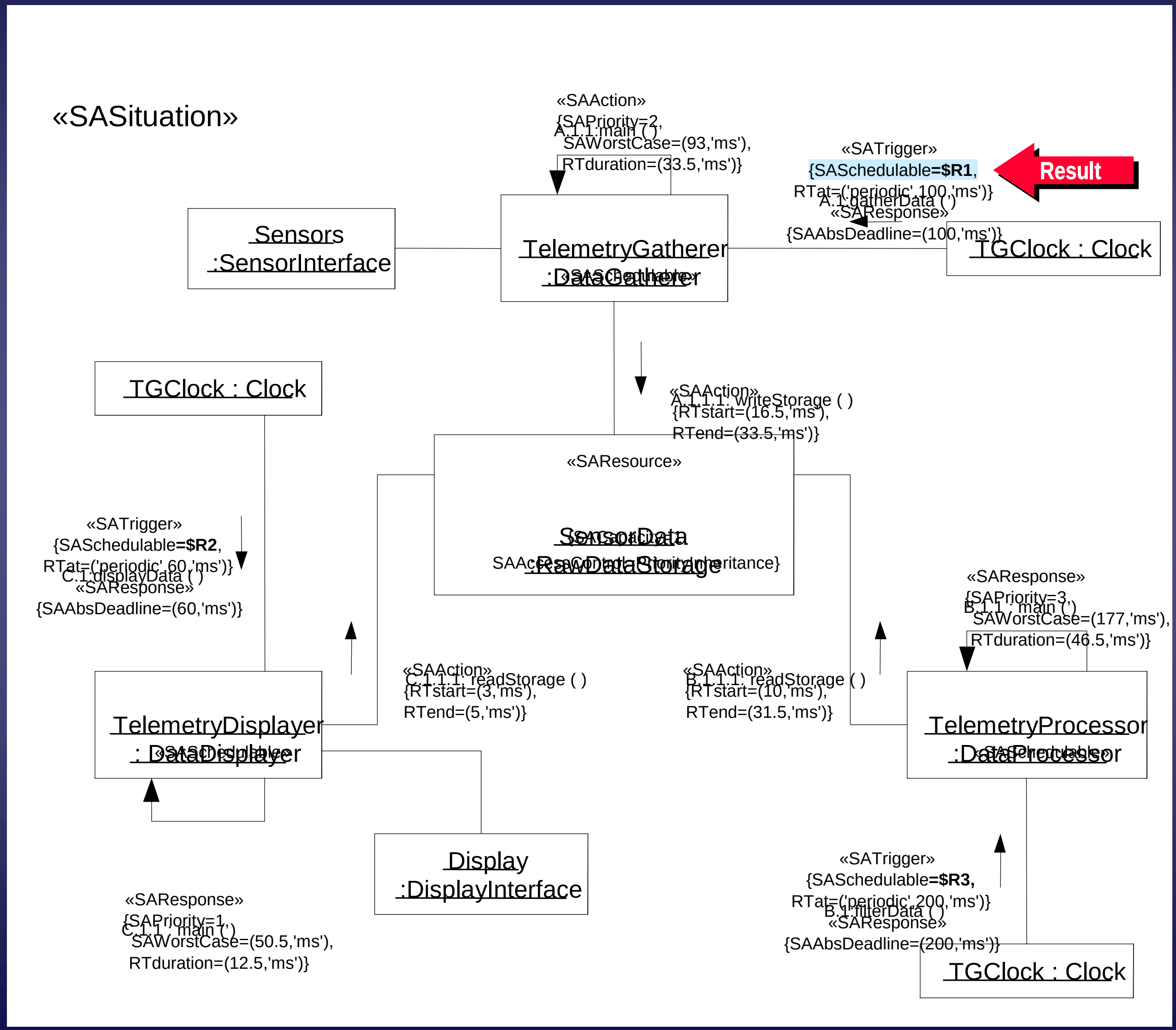
- Scheduling Policies:
  - Rate Monotonic, Deadline Monotonic, HKL, Fixed Priority, Minimum Laxity First, Maximize Accrued Utility, Minimum Slack Time
  - …may be extended in the future
- Access Control Policies:
  - FIFO, Priority Inheritance, No Preemption, Highest Lockers, Priority Ceiling
  - …may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

Example

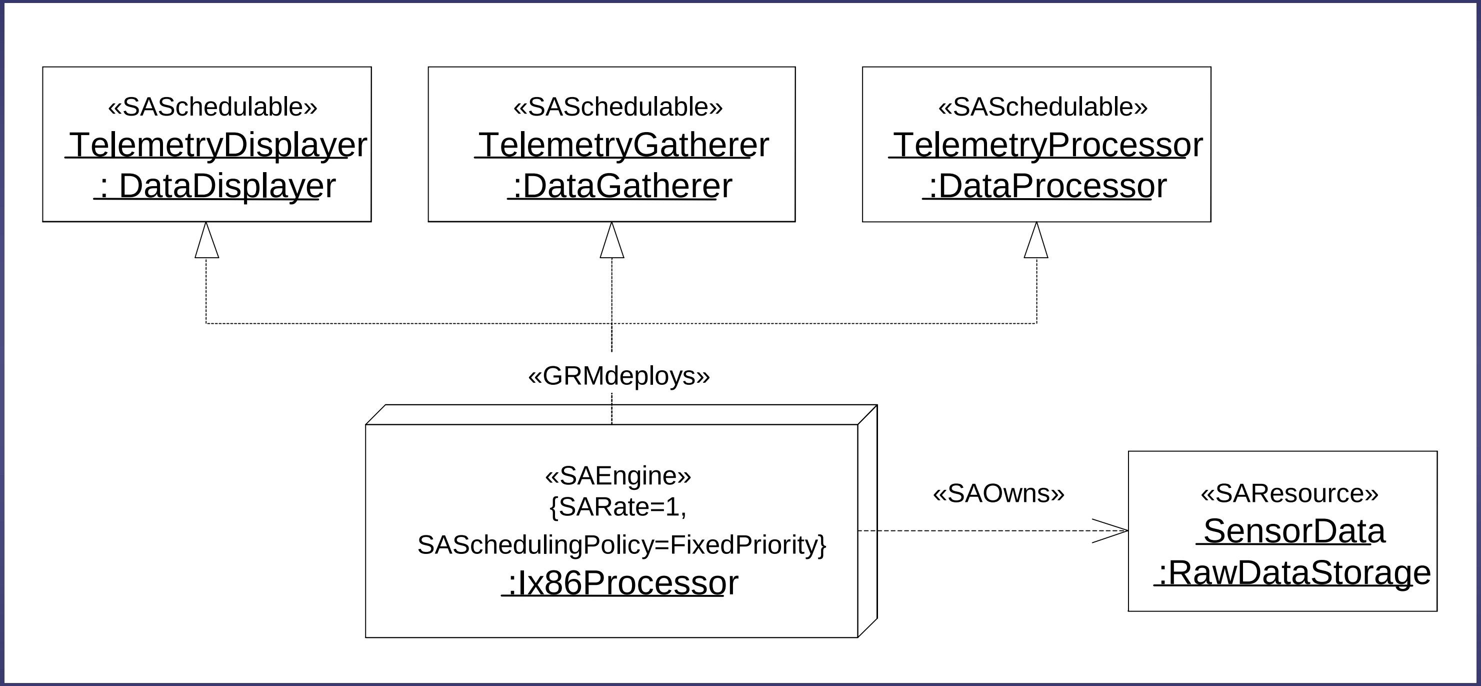
- A simple telemetry system with 3 cyclical tasks



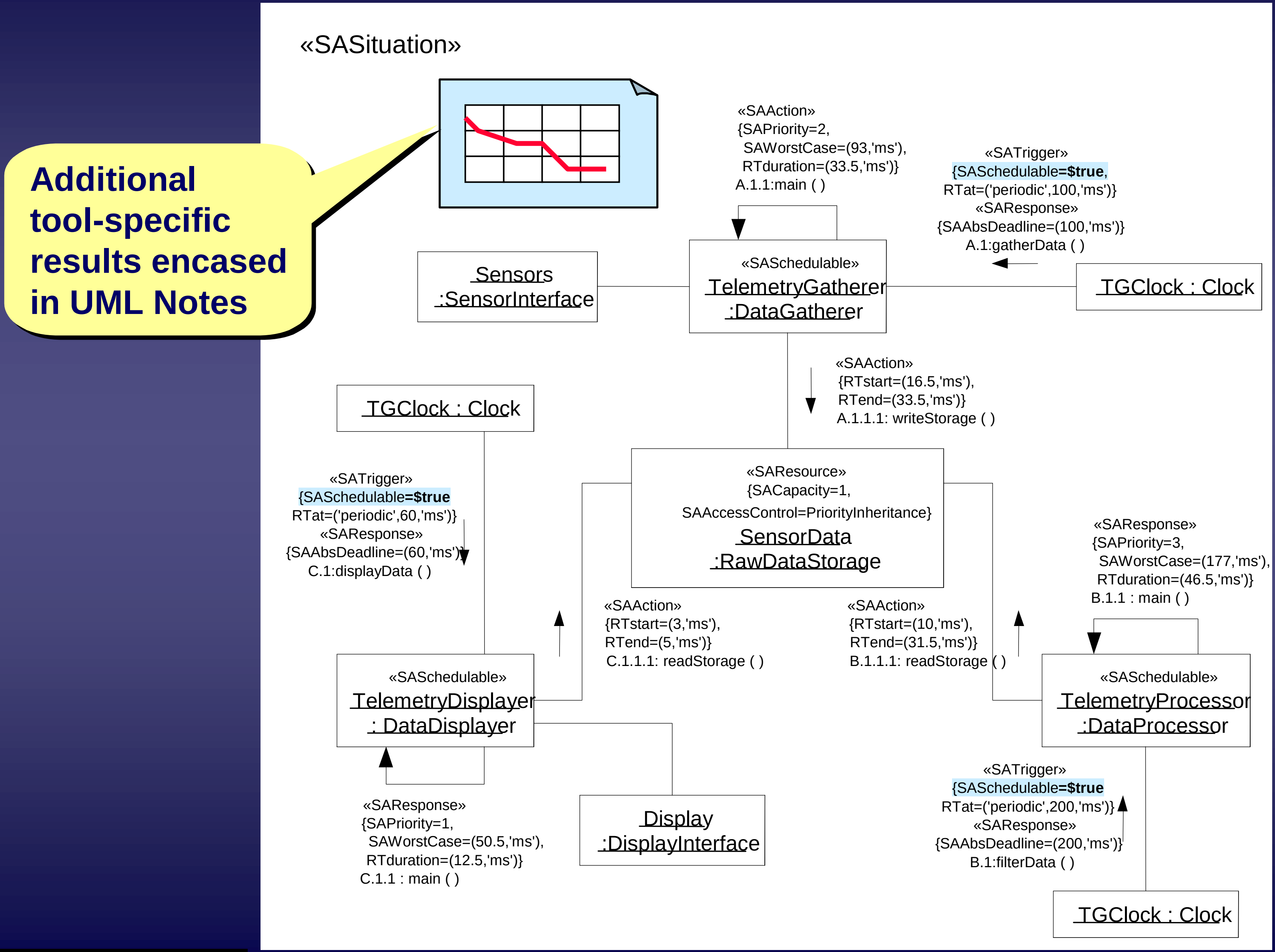
Example: Schedulability Annotations



Example: Deployment Specification



Example: Analysis Results



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

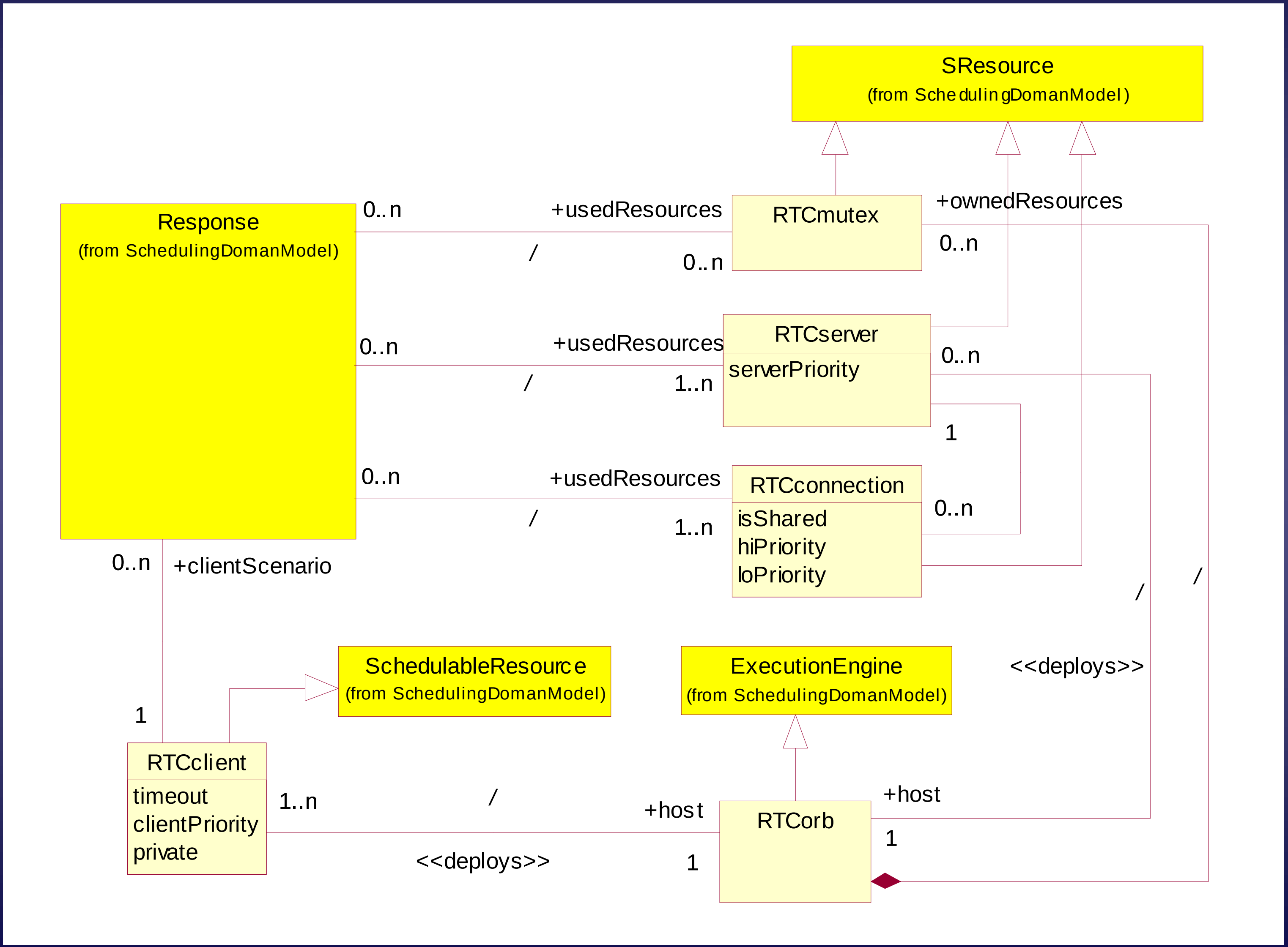
Defined Stereotypes (2 of 3)

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

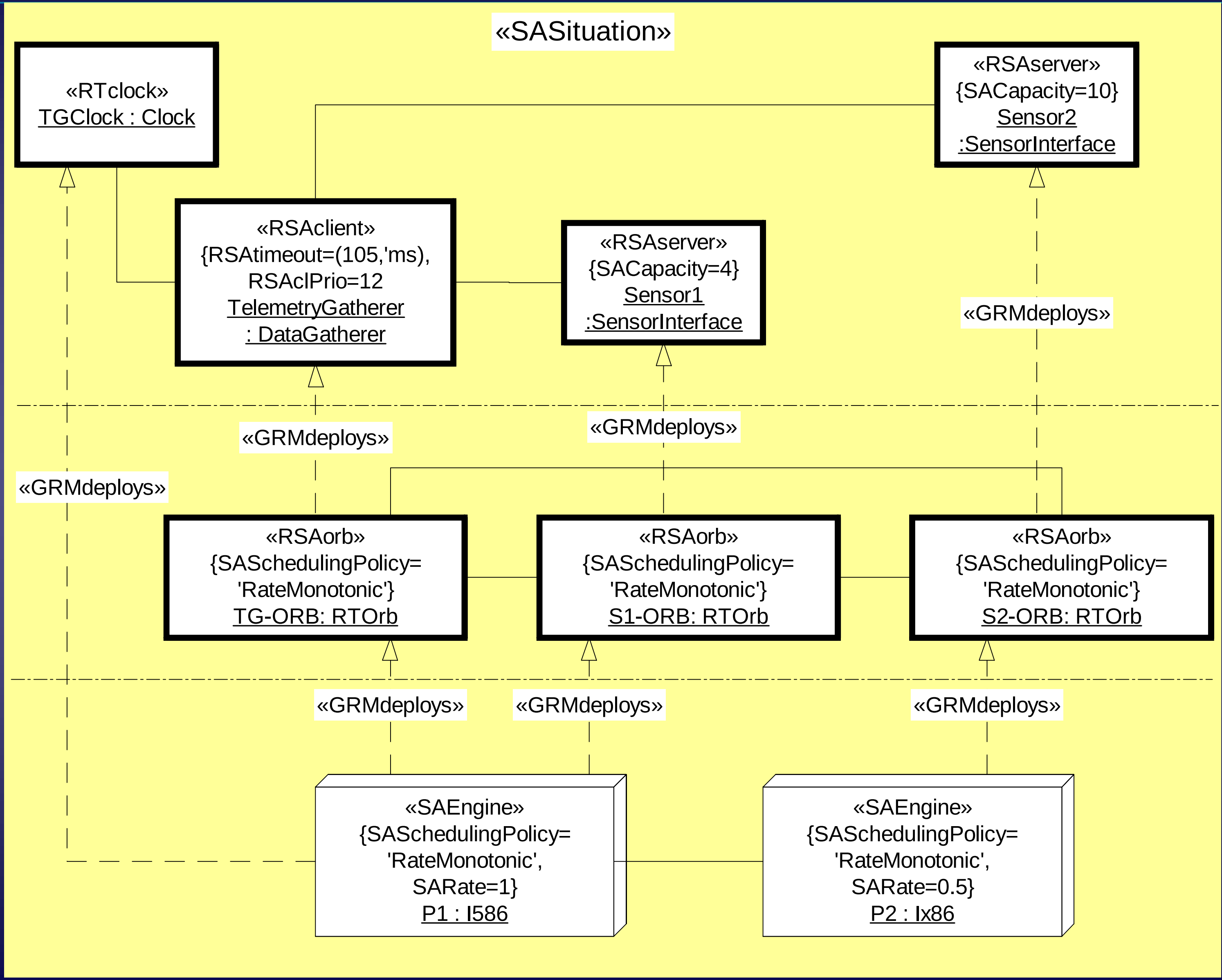
Defined Stereotypes (3 of 3)

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

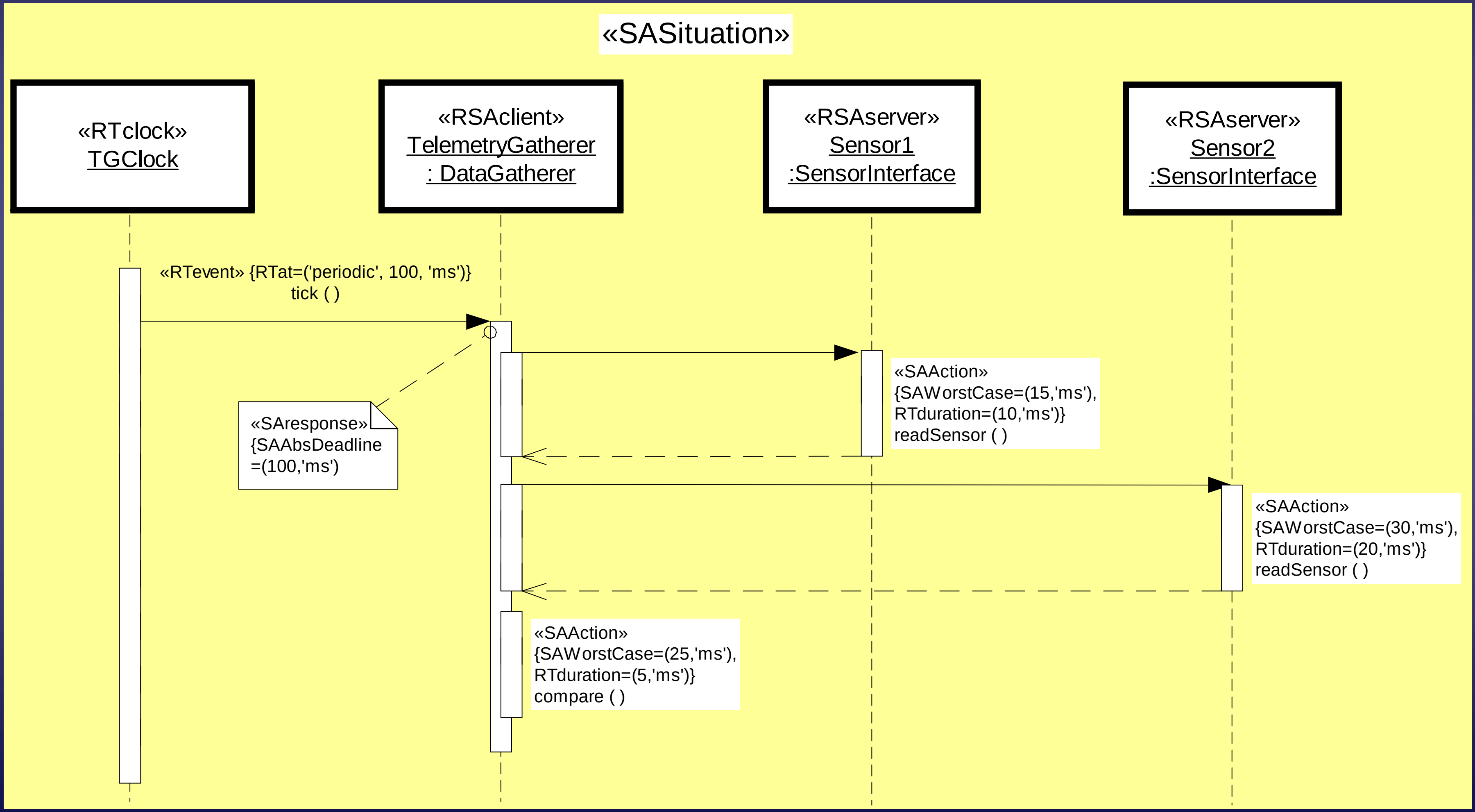
Real-Time CORBA: Schedulability Sub-Profile



Example: RT CORBA



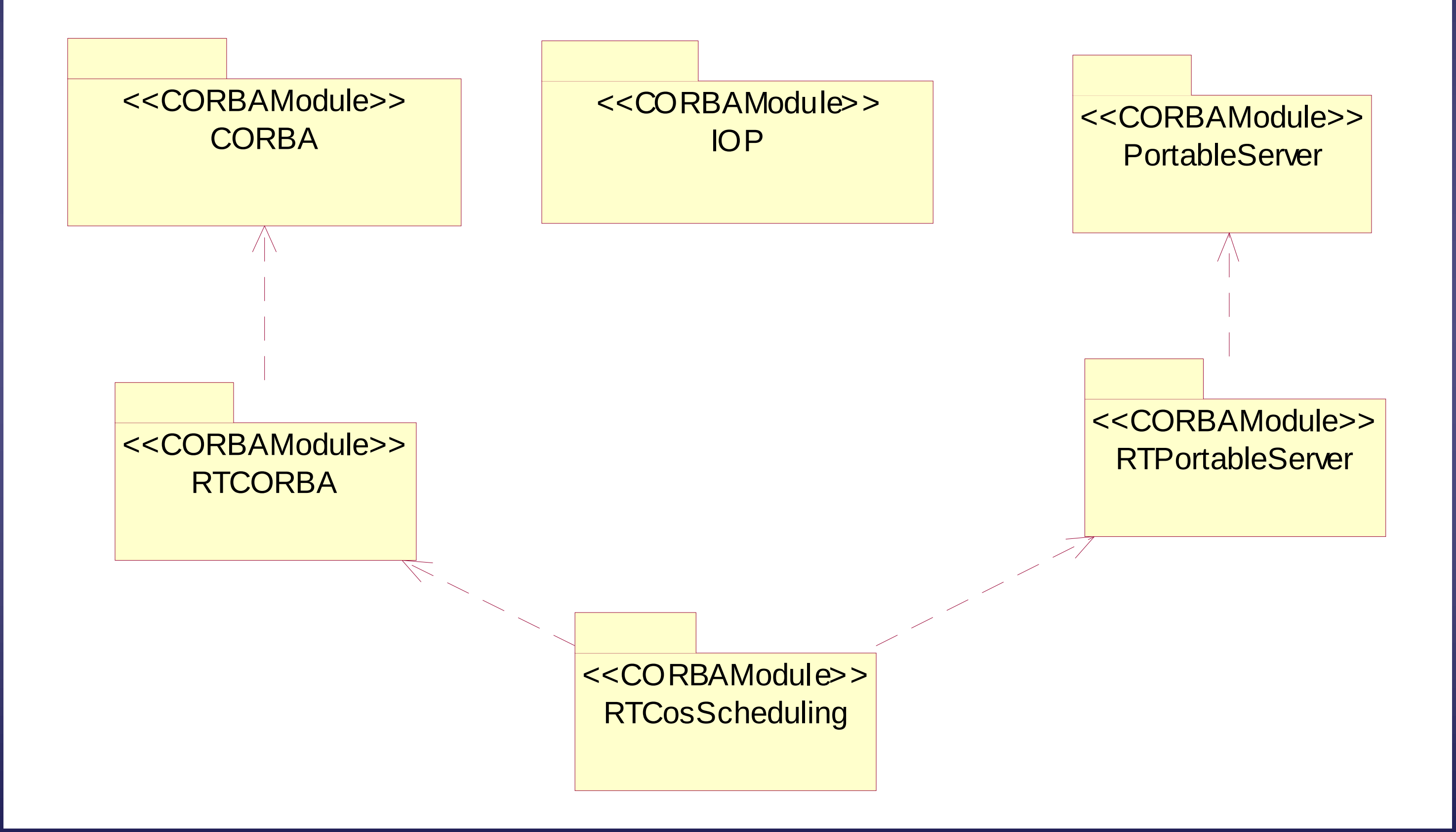
Example: RT CORBA Usage Scenario



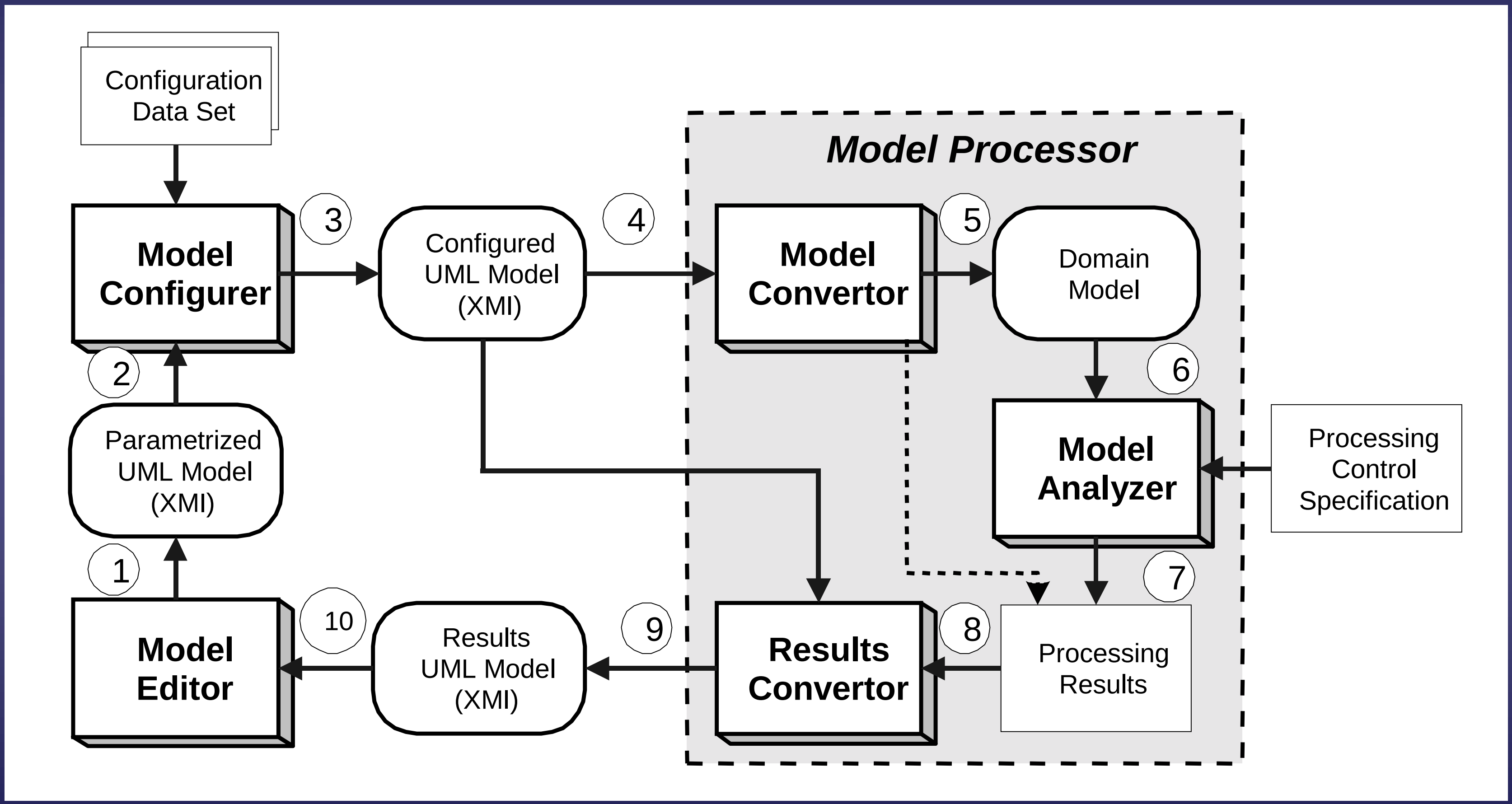
Defined Stereotypes

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

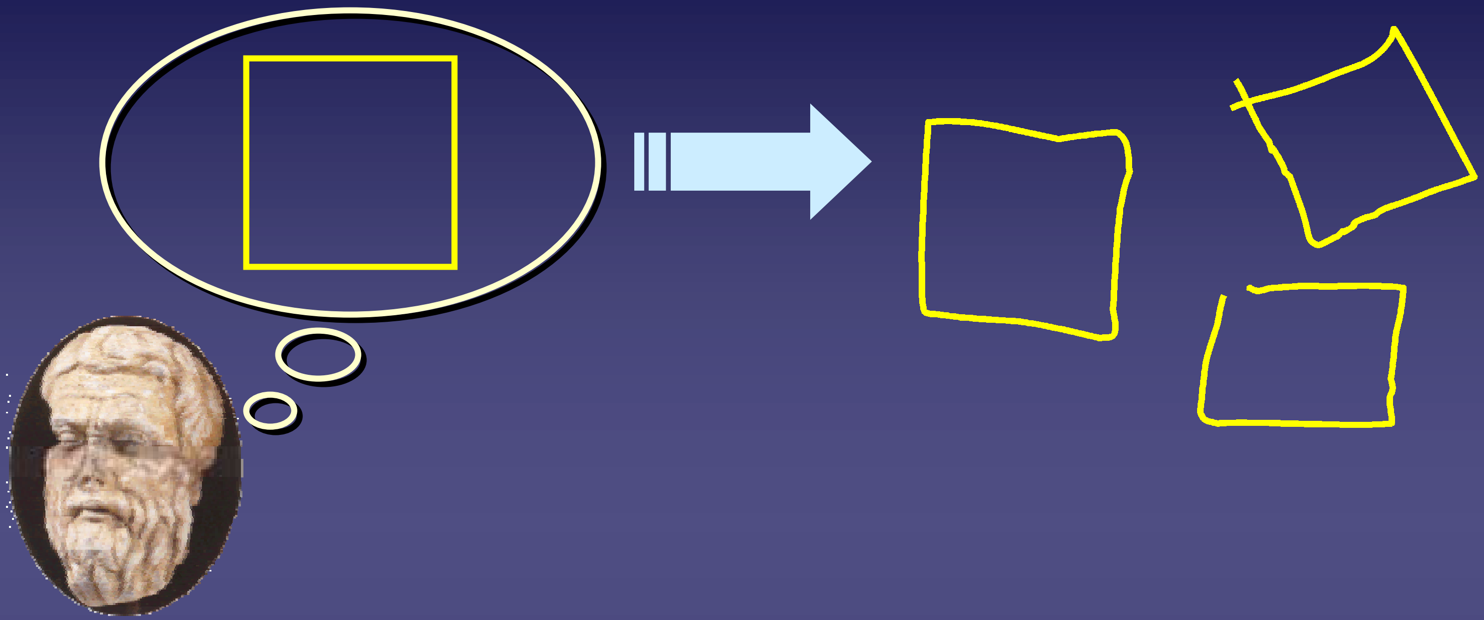
- The RT UML Profile defines a set of extensions for directly expressing real-time domain concepts in UML:
  - resources
  - concurrency mechanisms
  - time and timing mechanisms
- Furthermore, it allows the specification of quantitative aspects in the same models such that the models can be analyzed
  - 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?

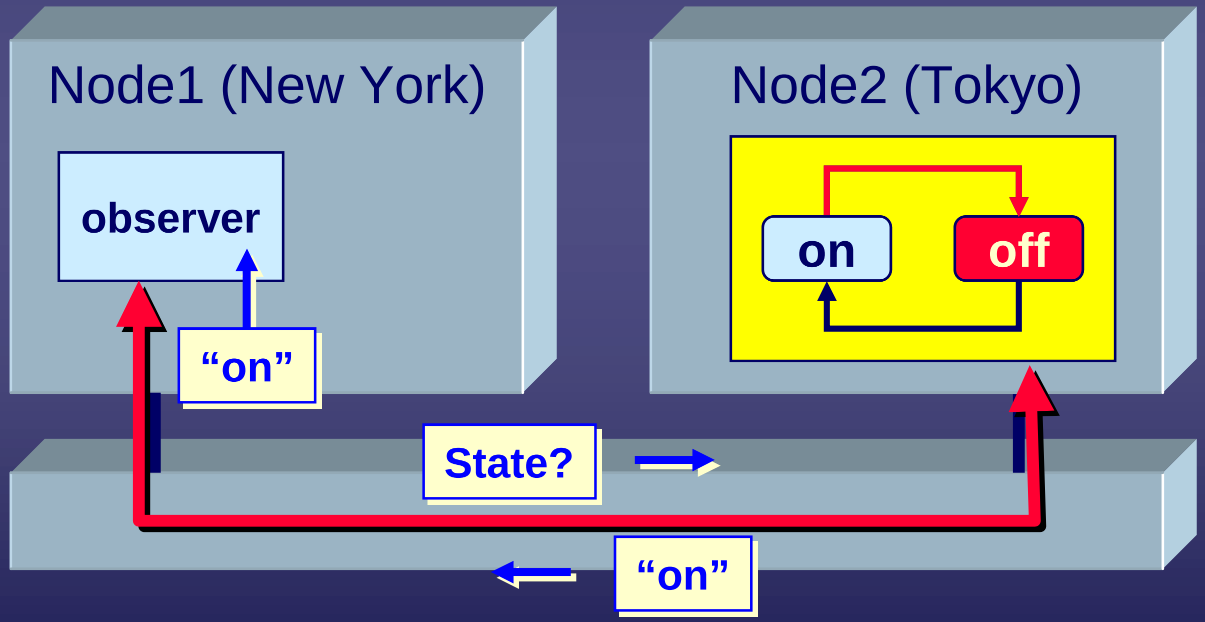
The Ideal and the Real



- 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)

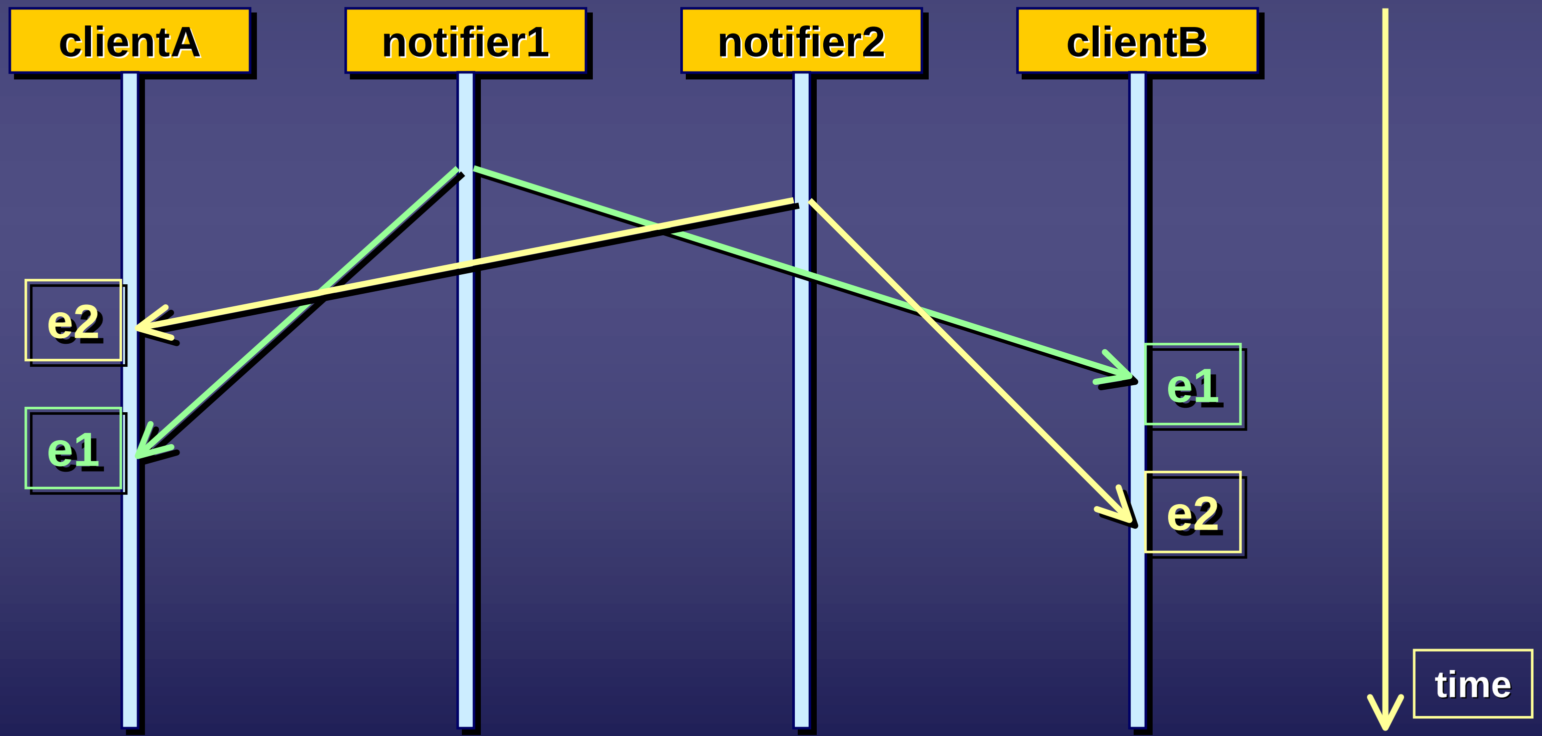
- Possibility of out-of-date state information due to lengthy (and variable) transmission delays



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

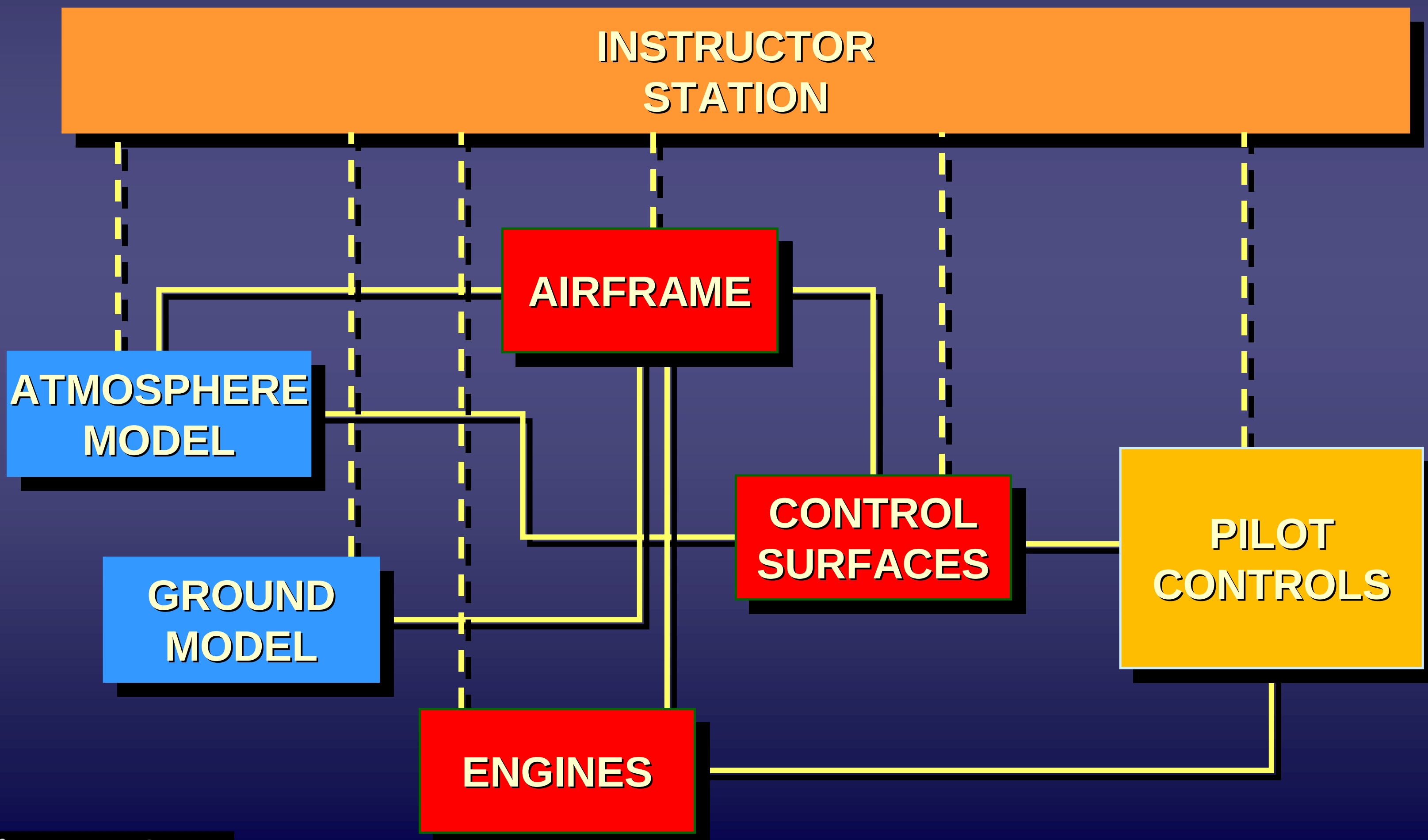
- Much of the complexity associated with these systems is the result of the "intrusion" of the inherently complex physical world into the idealized logical world of software

- *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?

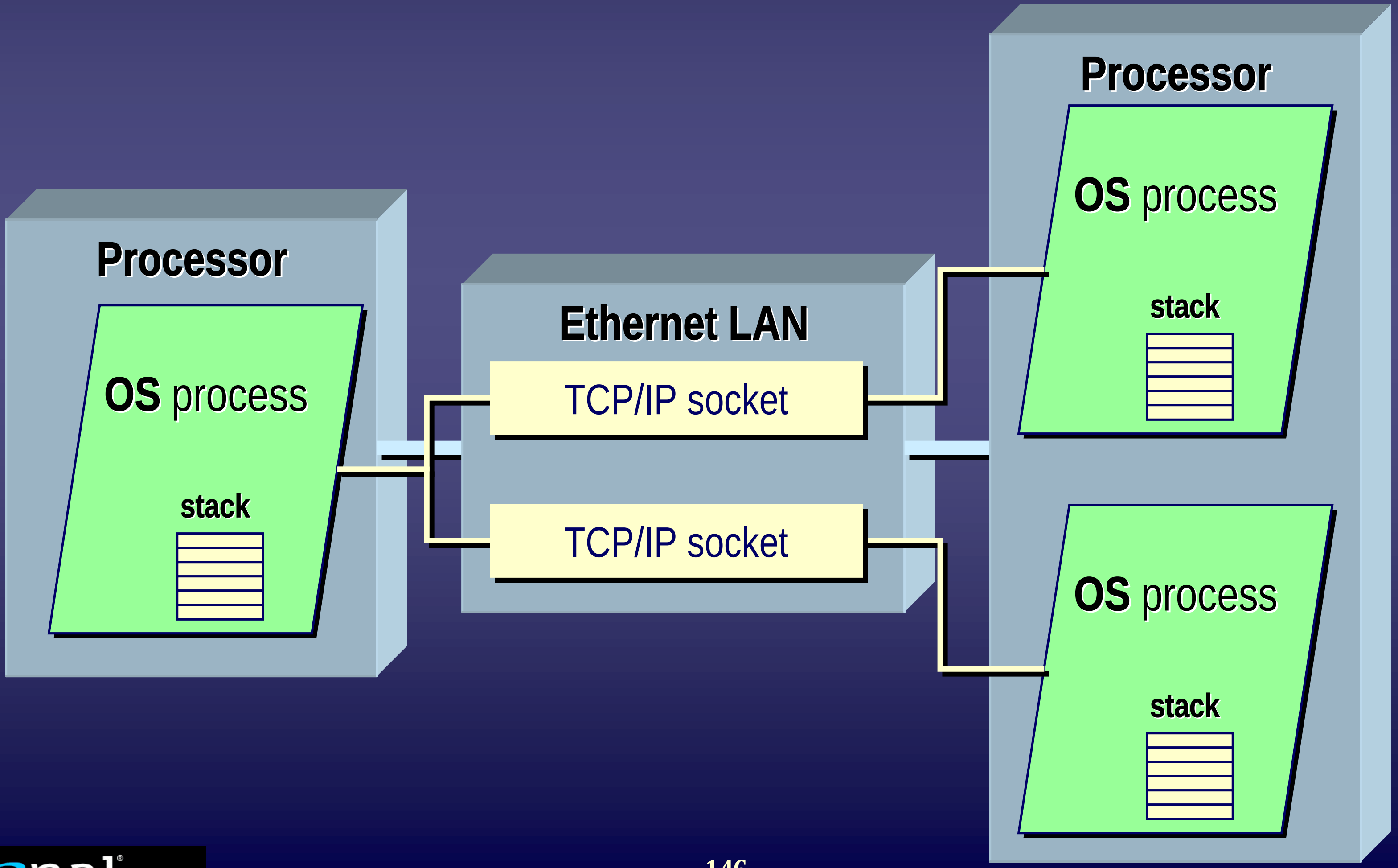
Logical (Conceptual) Viewpoint

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

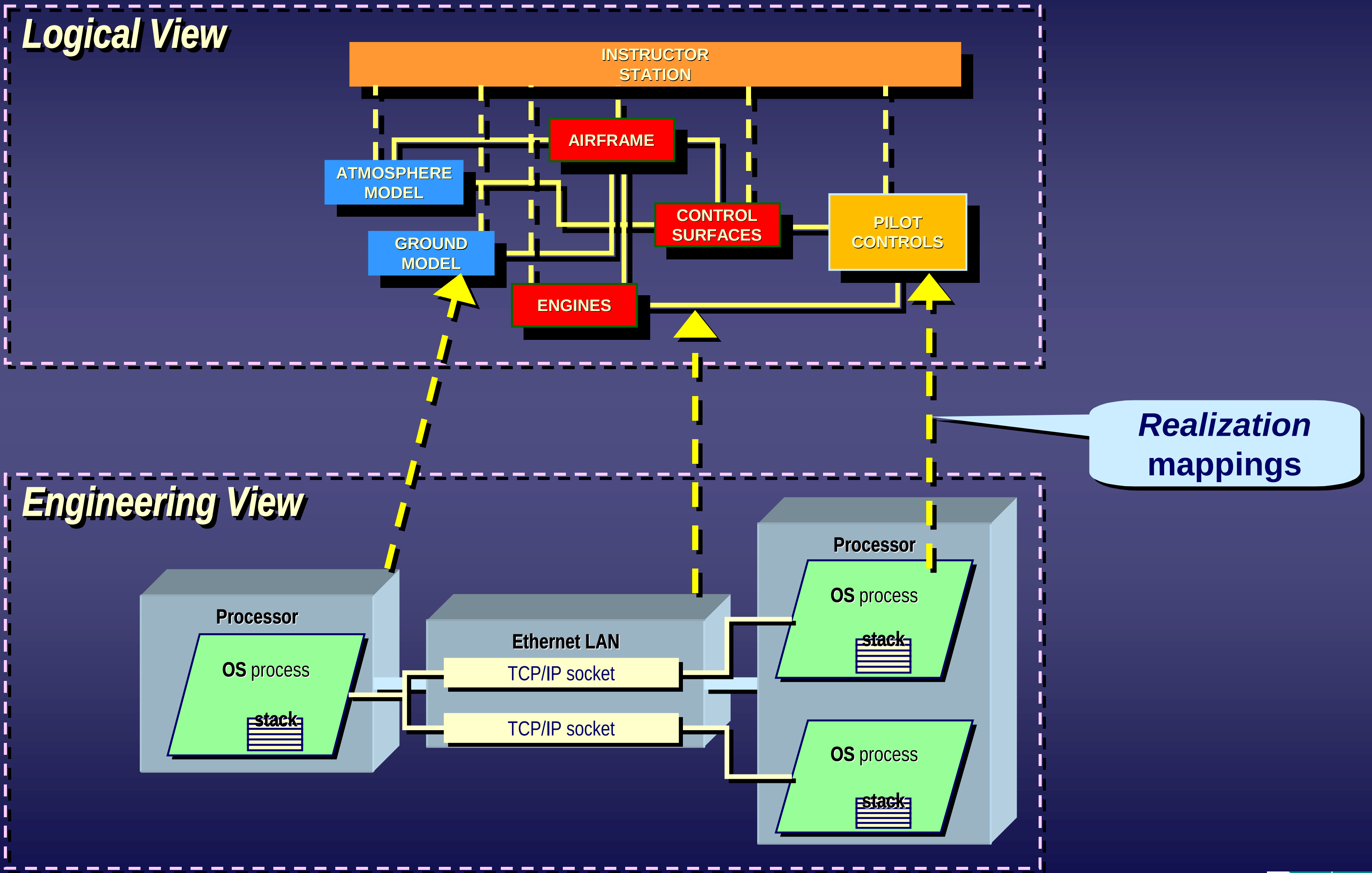


Engineering (Realization) Viewpoint

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

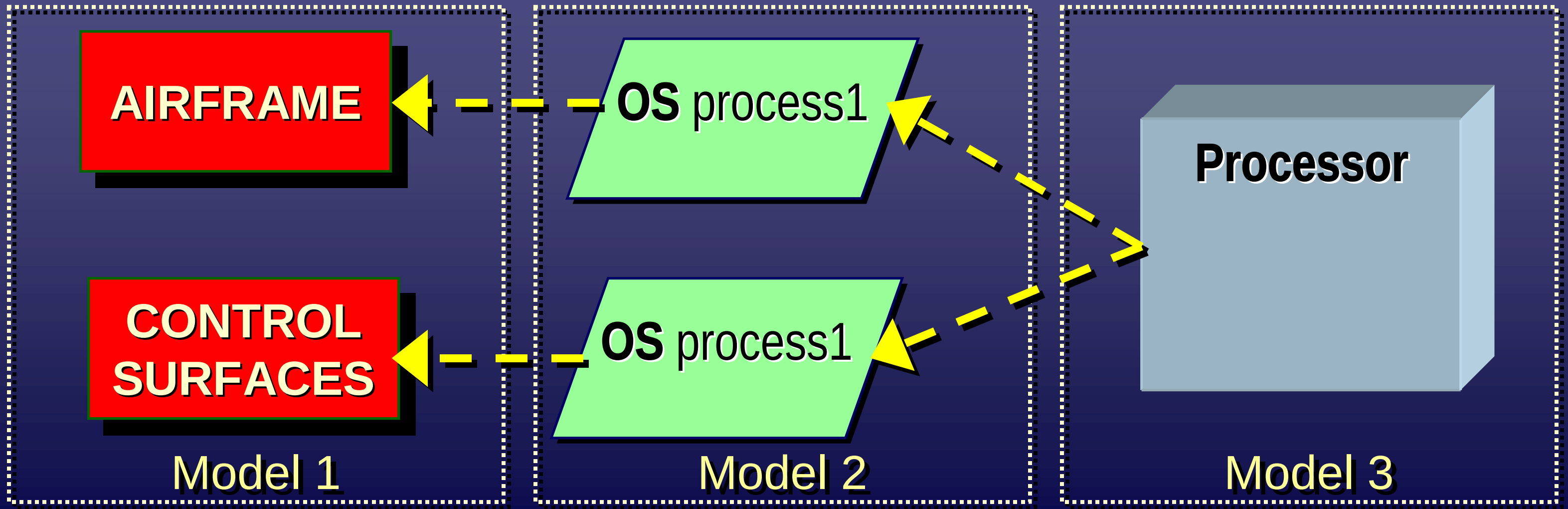


Views and Mappings



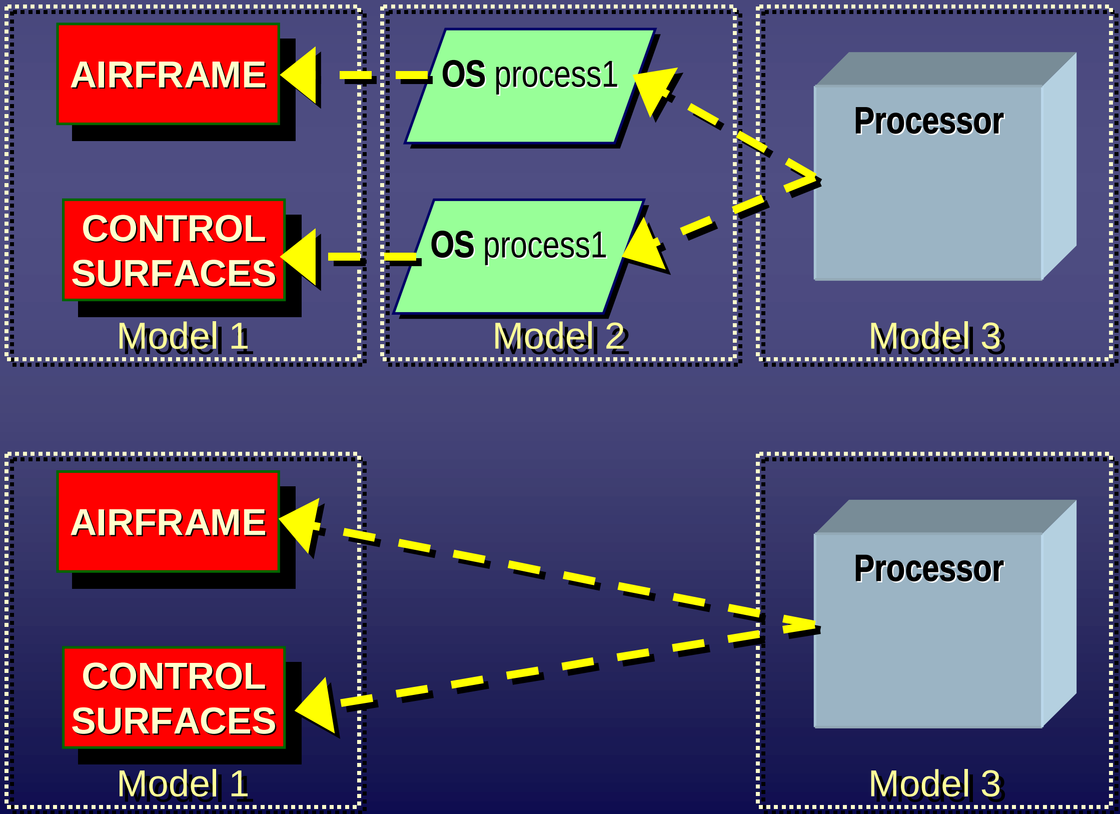
Realization Mappings

- 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 the corresponding engineering elements



Selecting a Level of Abstraction

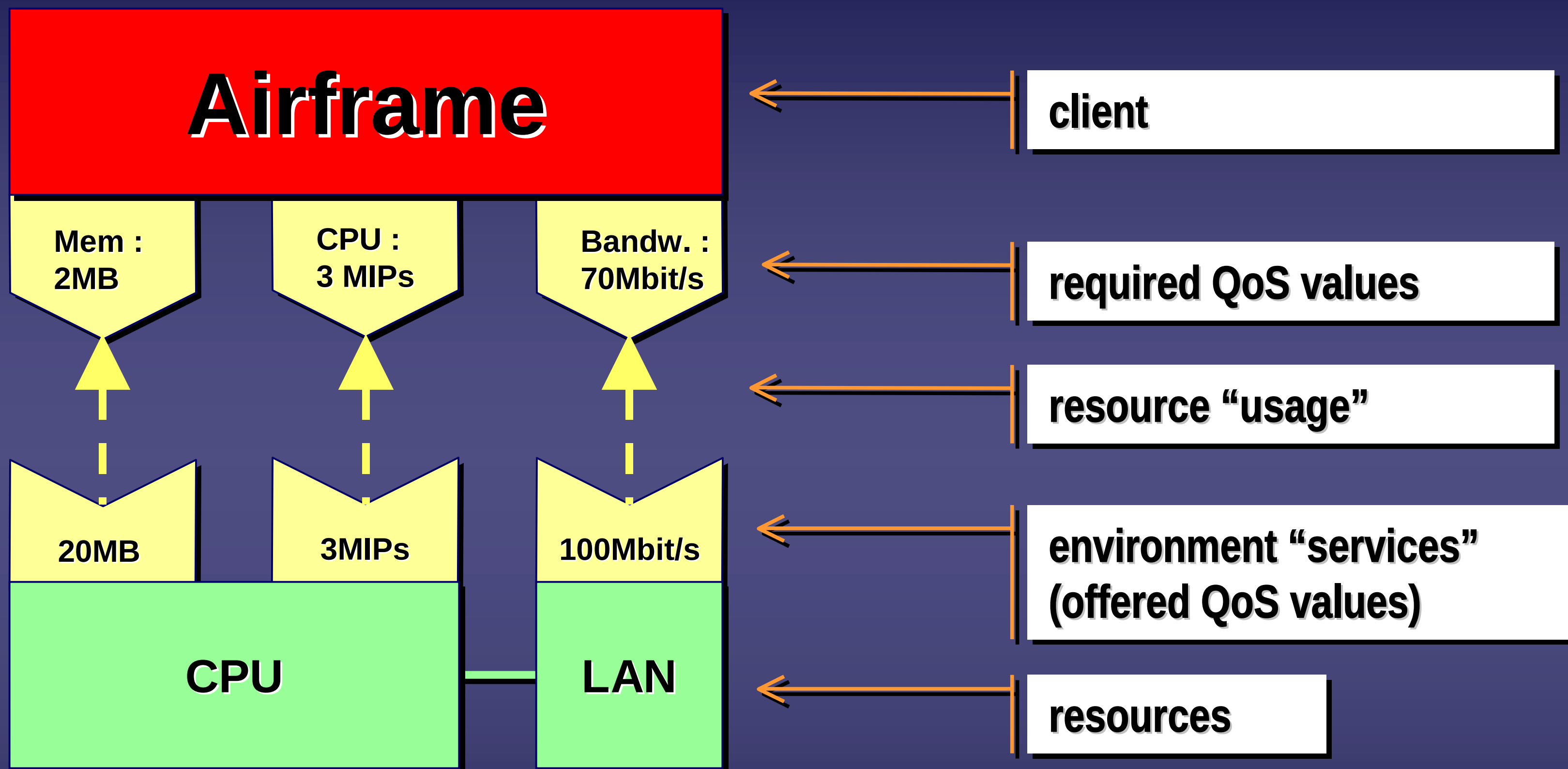
- Intermediate levels may be abstracted out
  - depends on the desired granularity of modeling
  - affects the semantics of the realization relationship



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 long will it take? How much 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

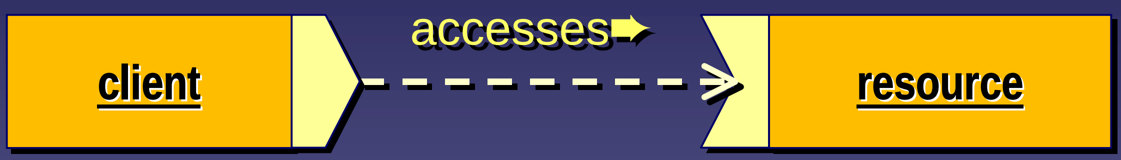
The Resource Model and Realization



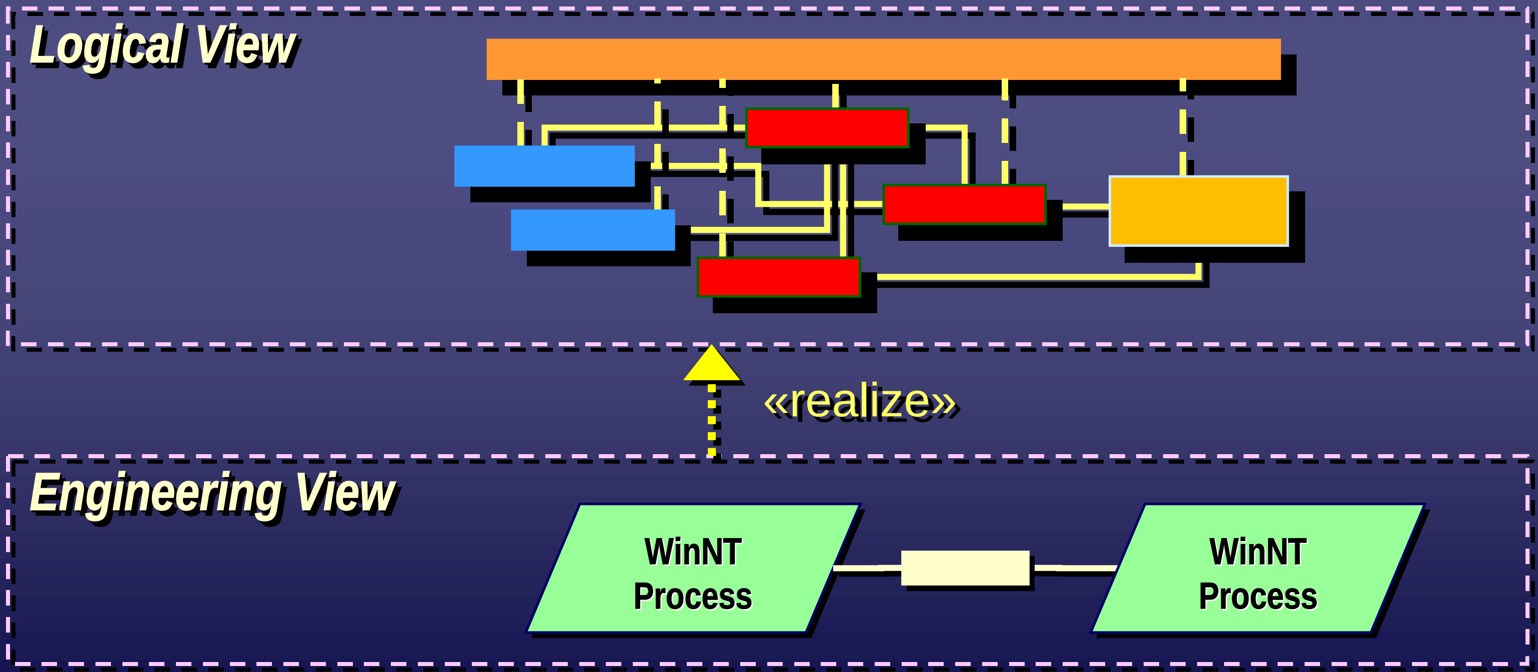
⇒ *The same QoS framework can be used for quantifying realization relationships*

Two Interpretations of Resource Model

- The peer interpretation

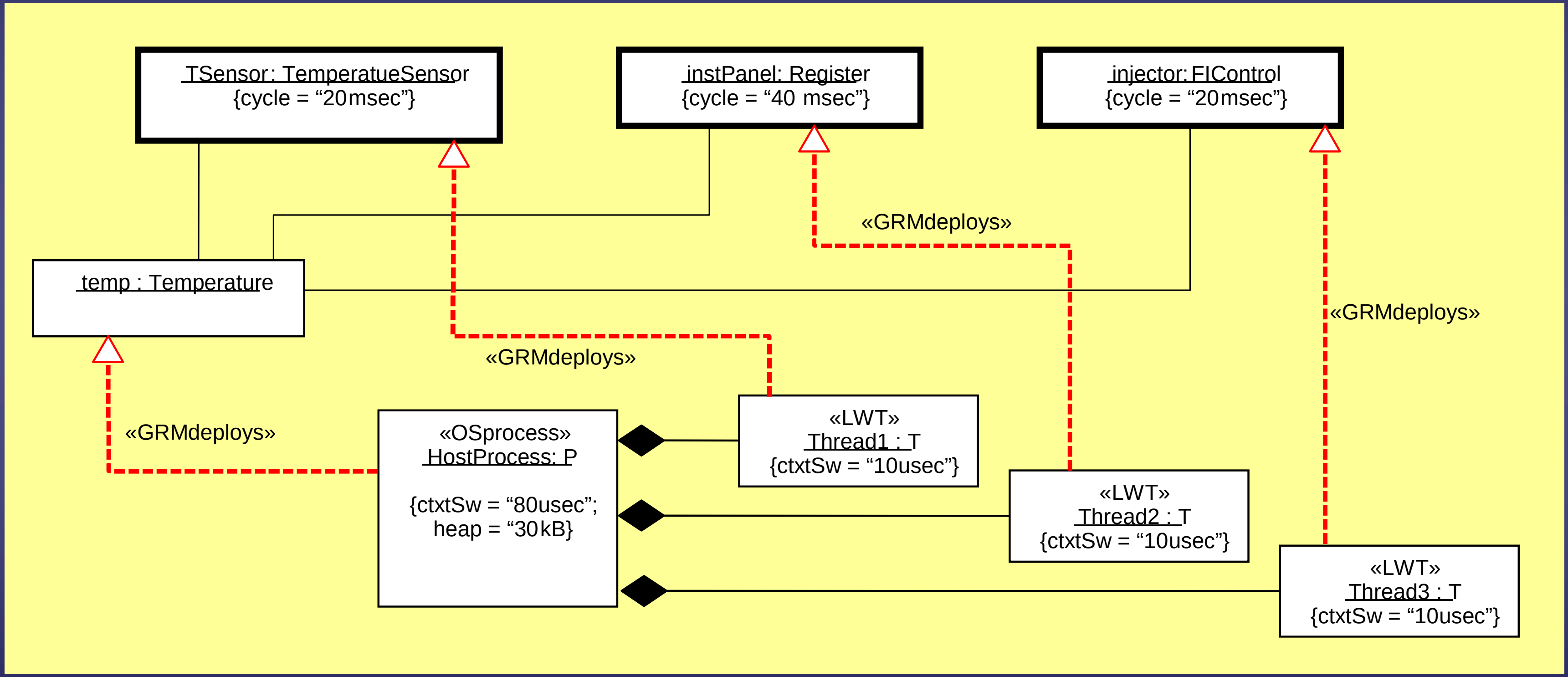


- The layered interpretation (the 2-viewpoint model)

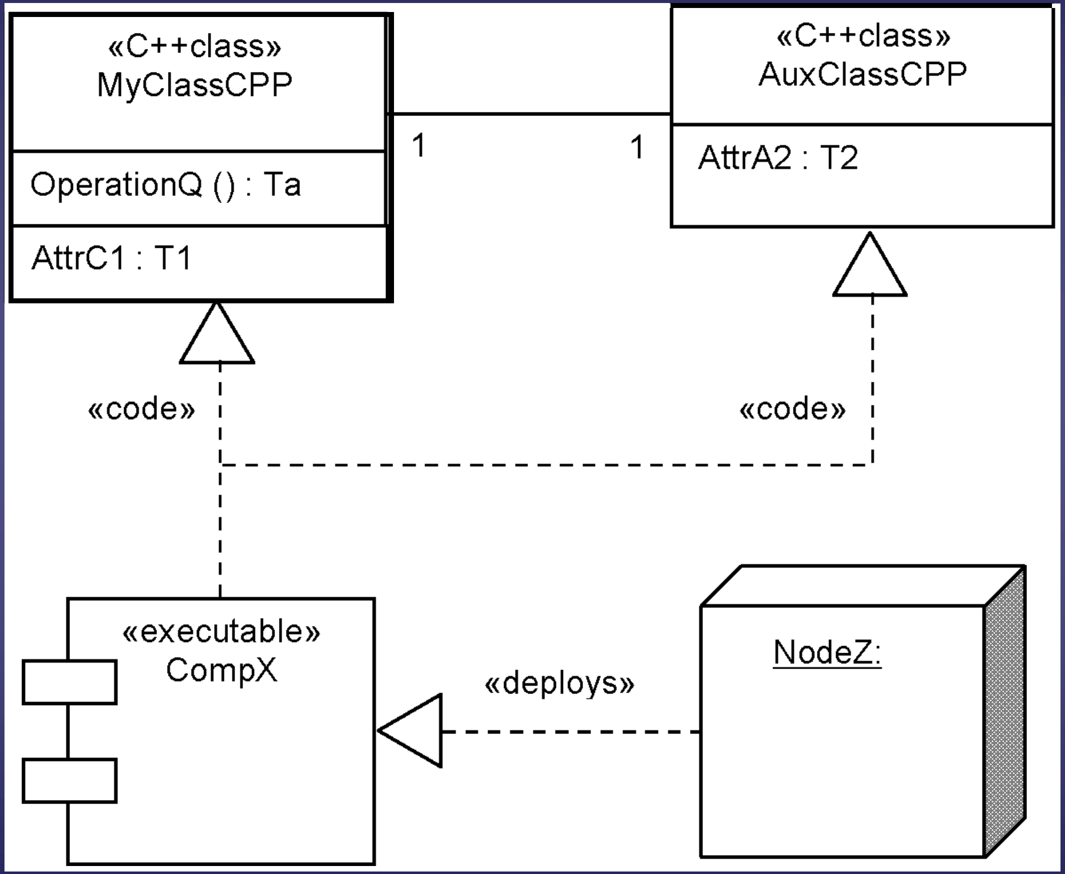


Example: Realization Relationships

- For sophisticated multi-layer deployment modeling

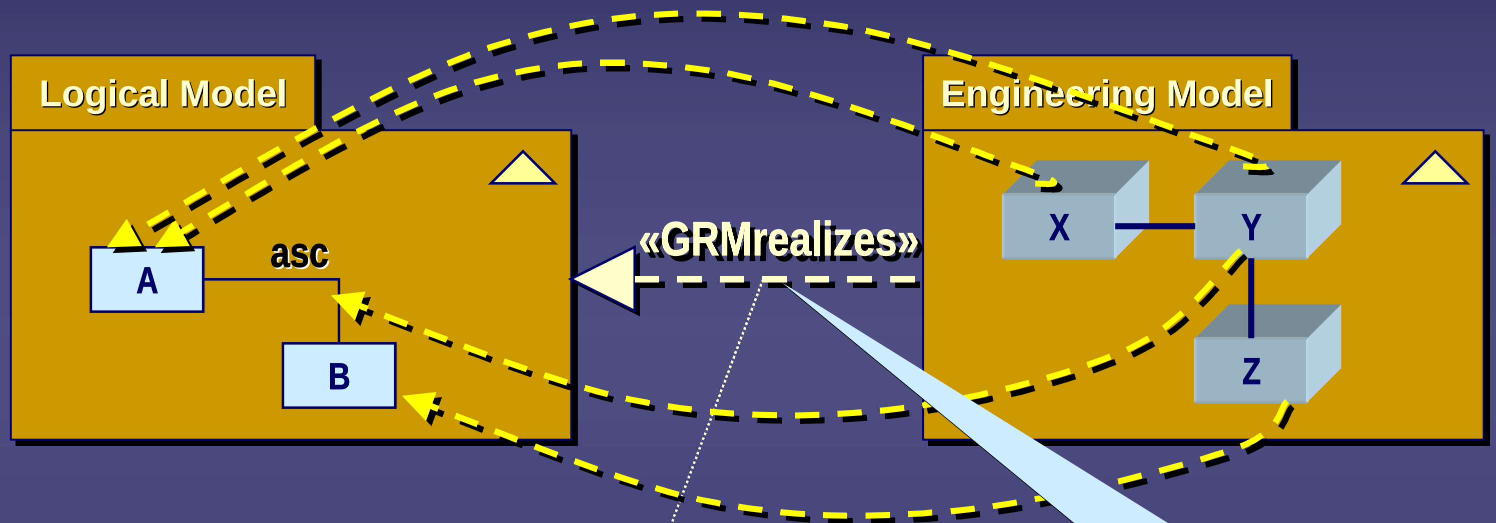


Forms of Realization



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

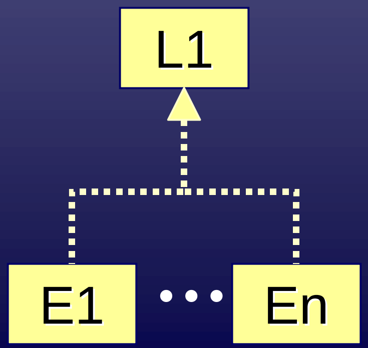
A stereotype of the UML realizes relationship

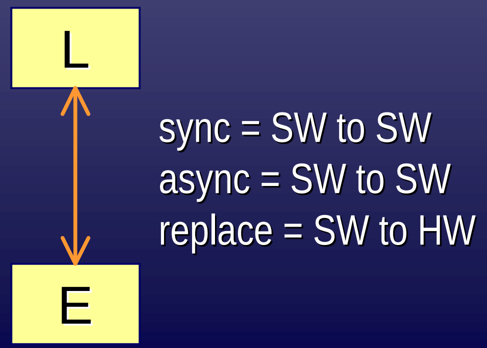
deployment table

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)

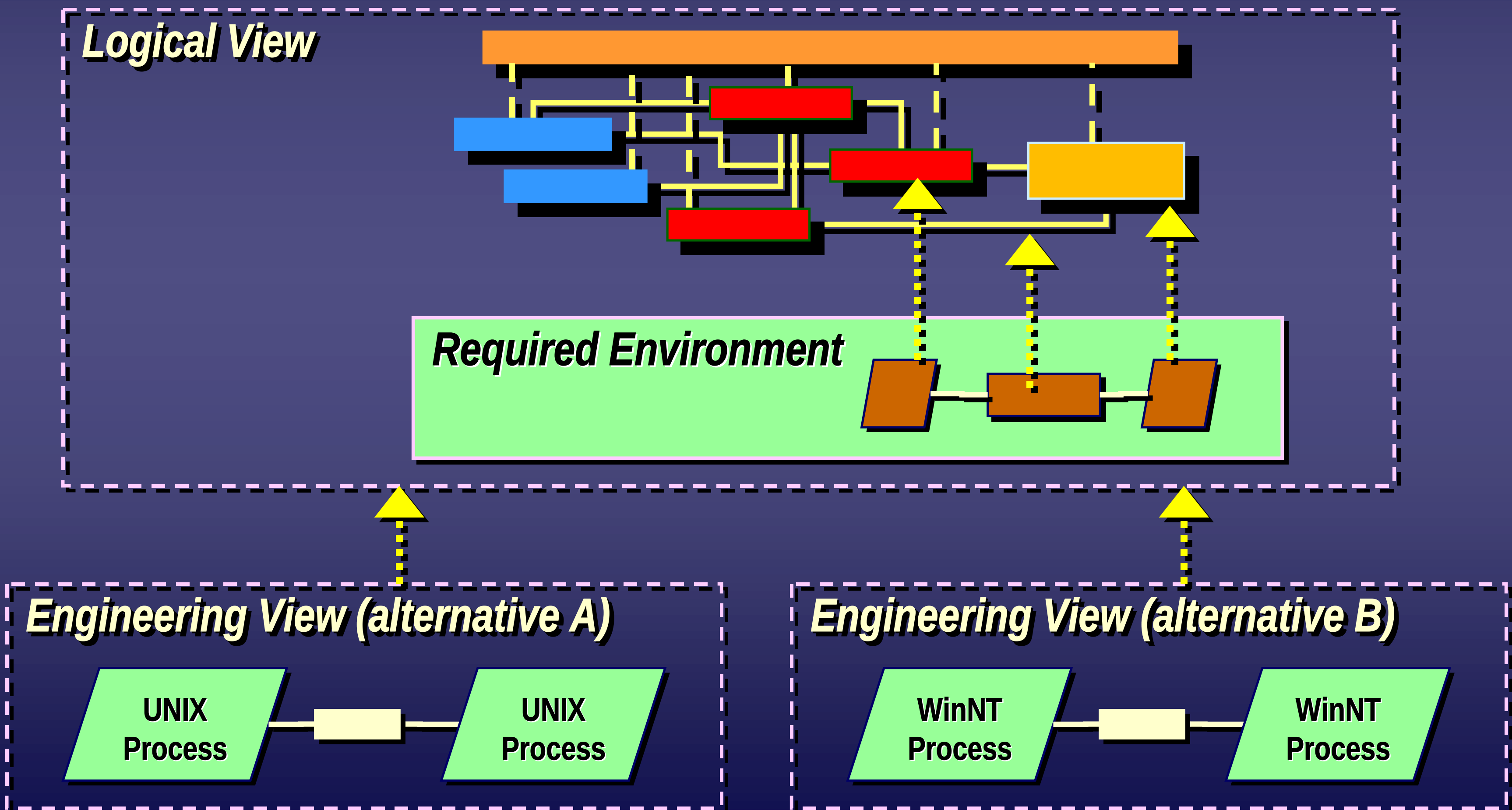
- *Analysis and design of software systems based on use of*
  - *Models*
  - *QoS specifications (accounting for physical properties)*
  - *Quantitative analysis techniques and simulation*
- Complements any model-based development method
- Advantages:
  - Higher reliability (simplification due to modeling)
  - 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*

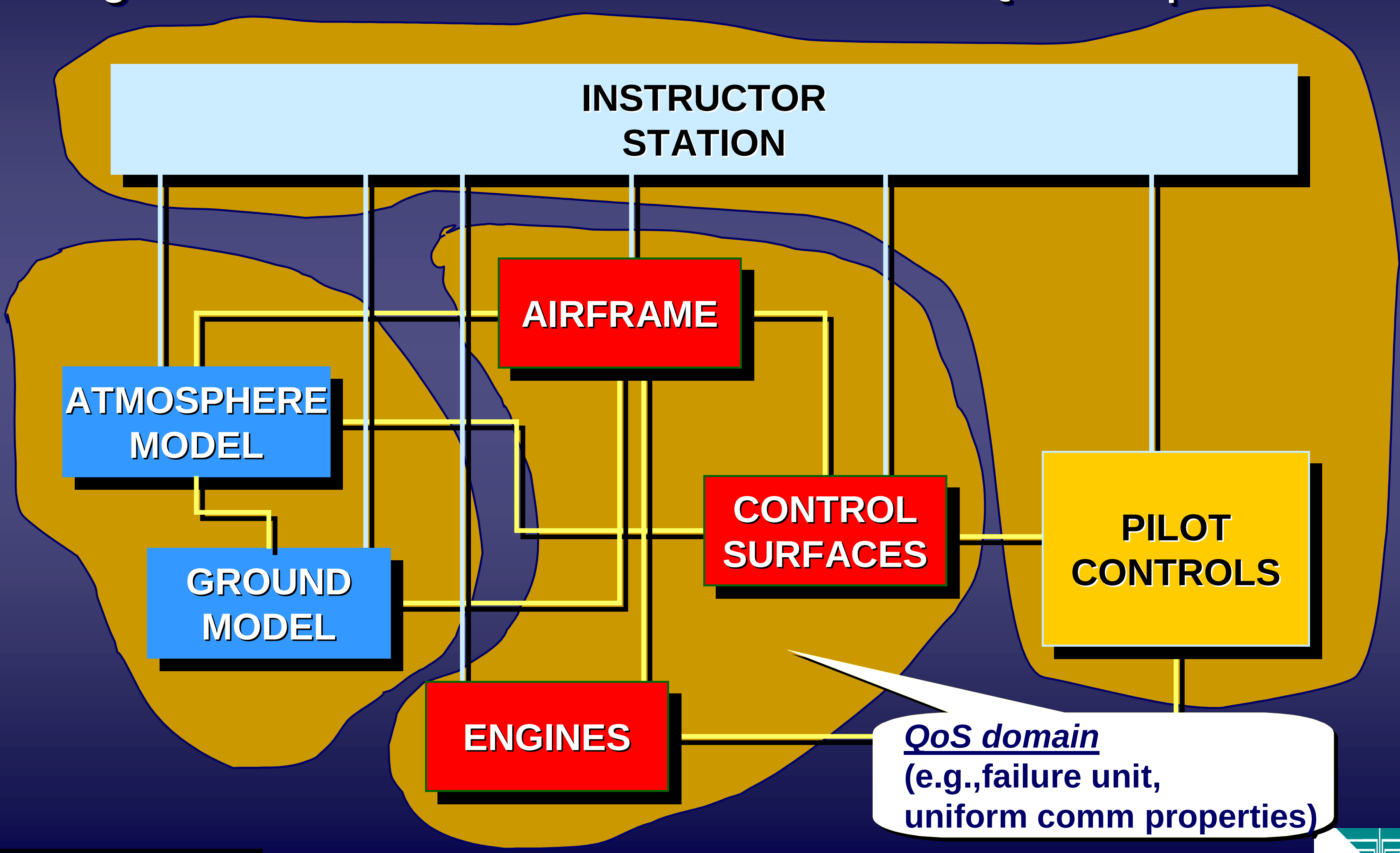
Viewpoint Separation

- *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

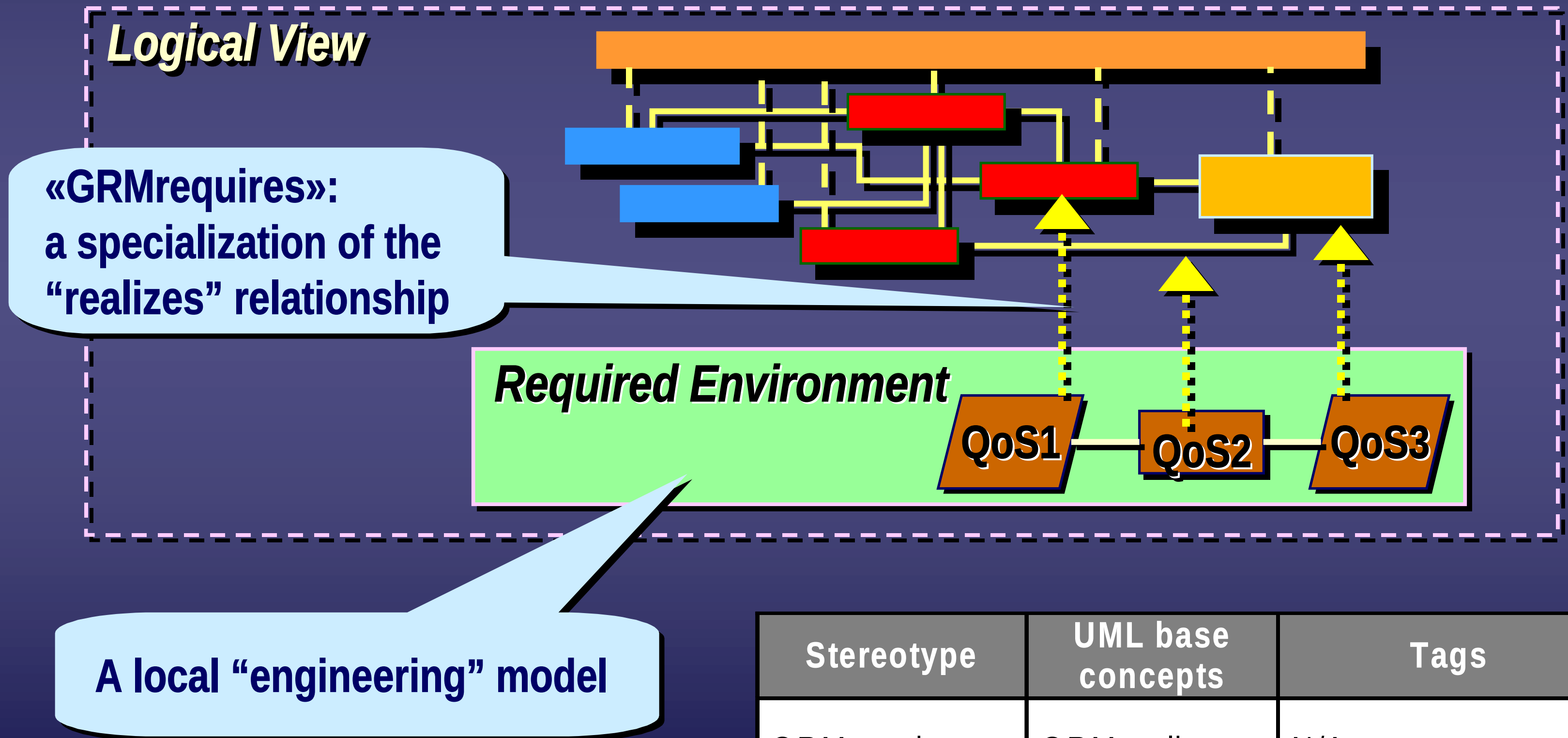


QoS Domains

- 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

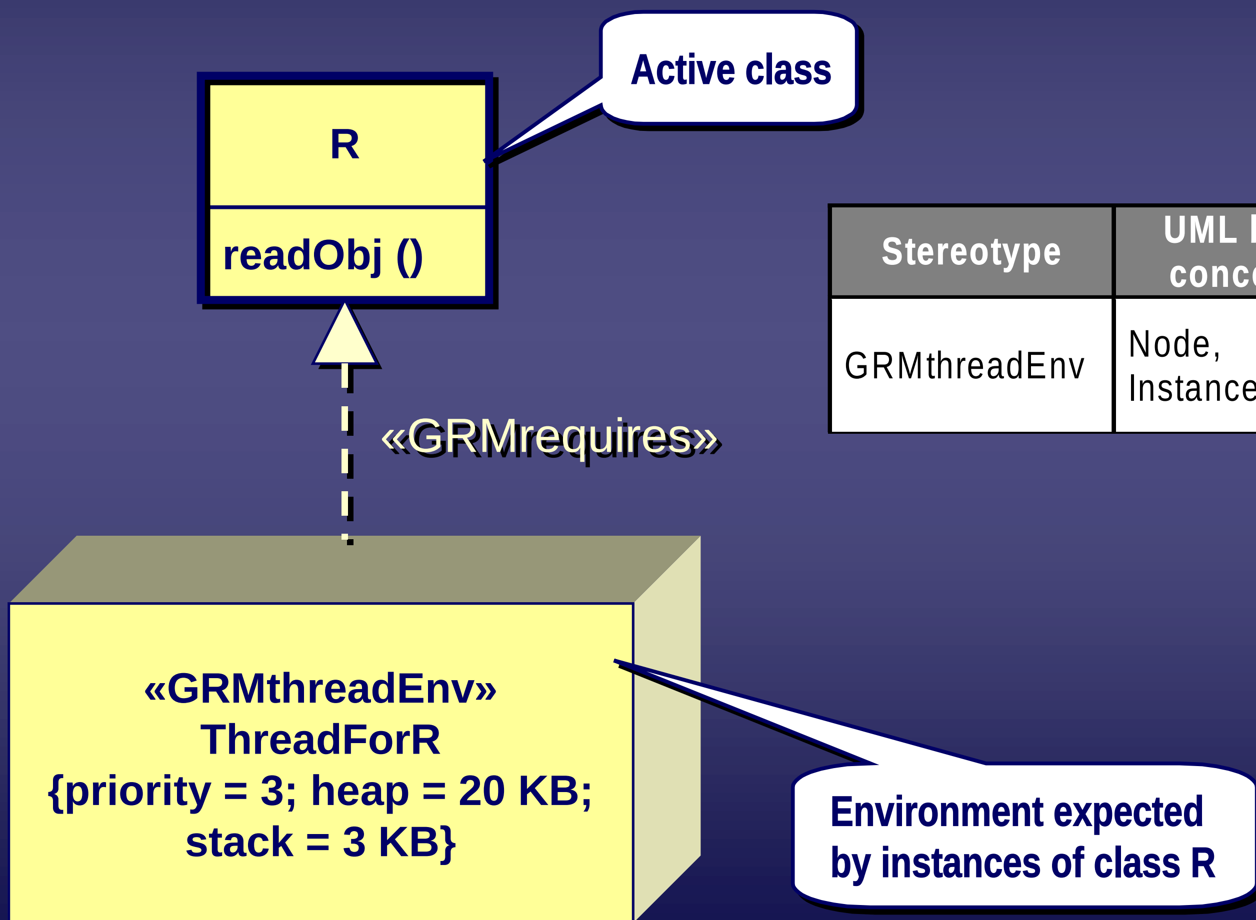
- Similar to realization: mapping of logical elements to a desired (required) engineering environment



Stereotype	UML base concepts	Tags
GRMrequires	GRMrealizes	N/A

Example: QoS Domain for an Active Object

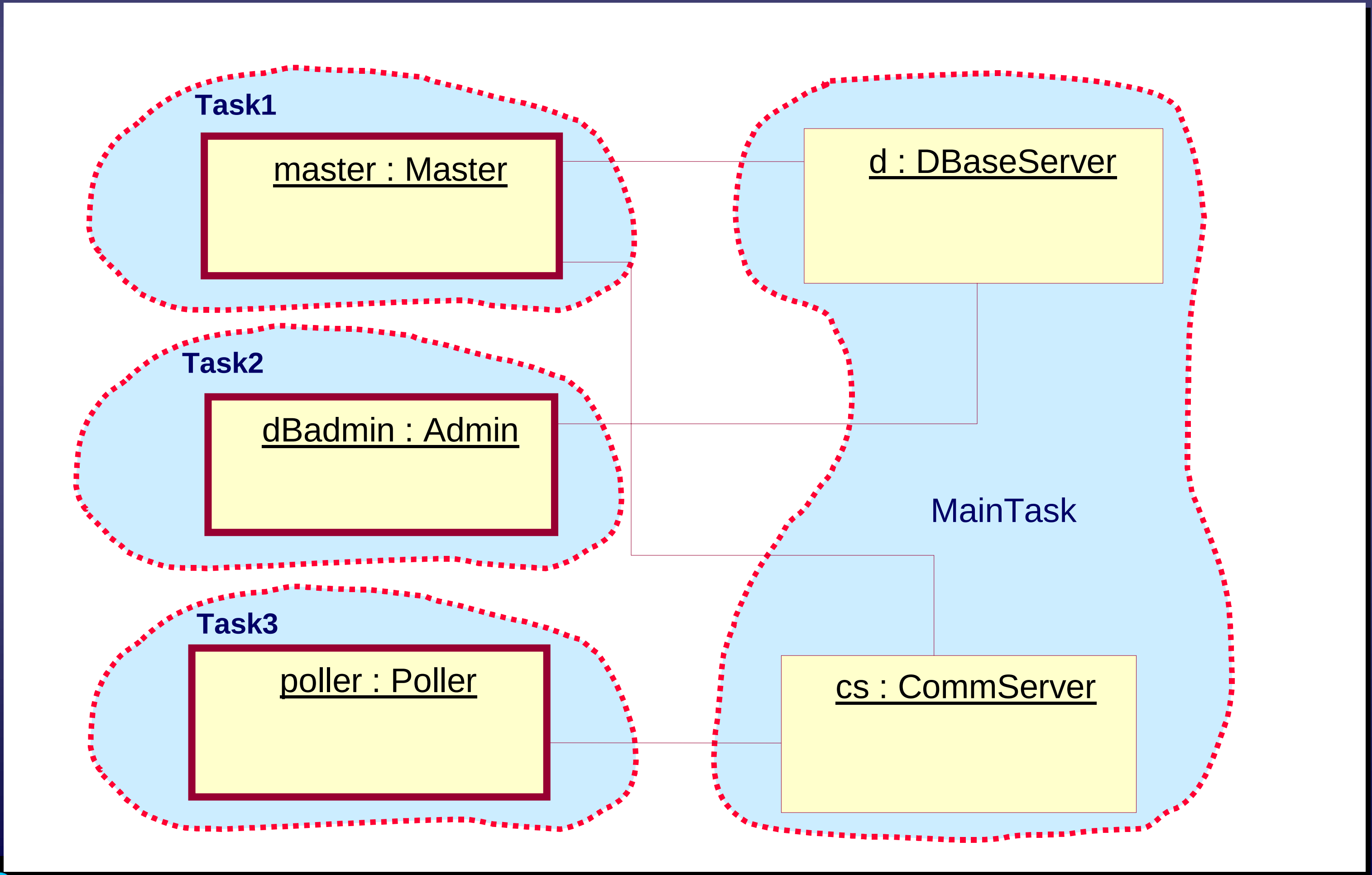
- Using a stereotype of Node
  - in conjunction with the “required environment” relationship



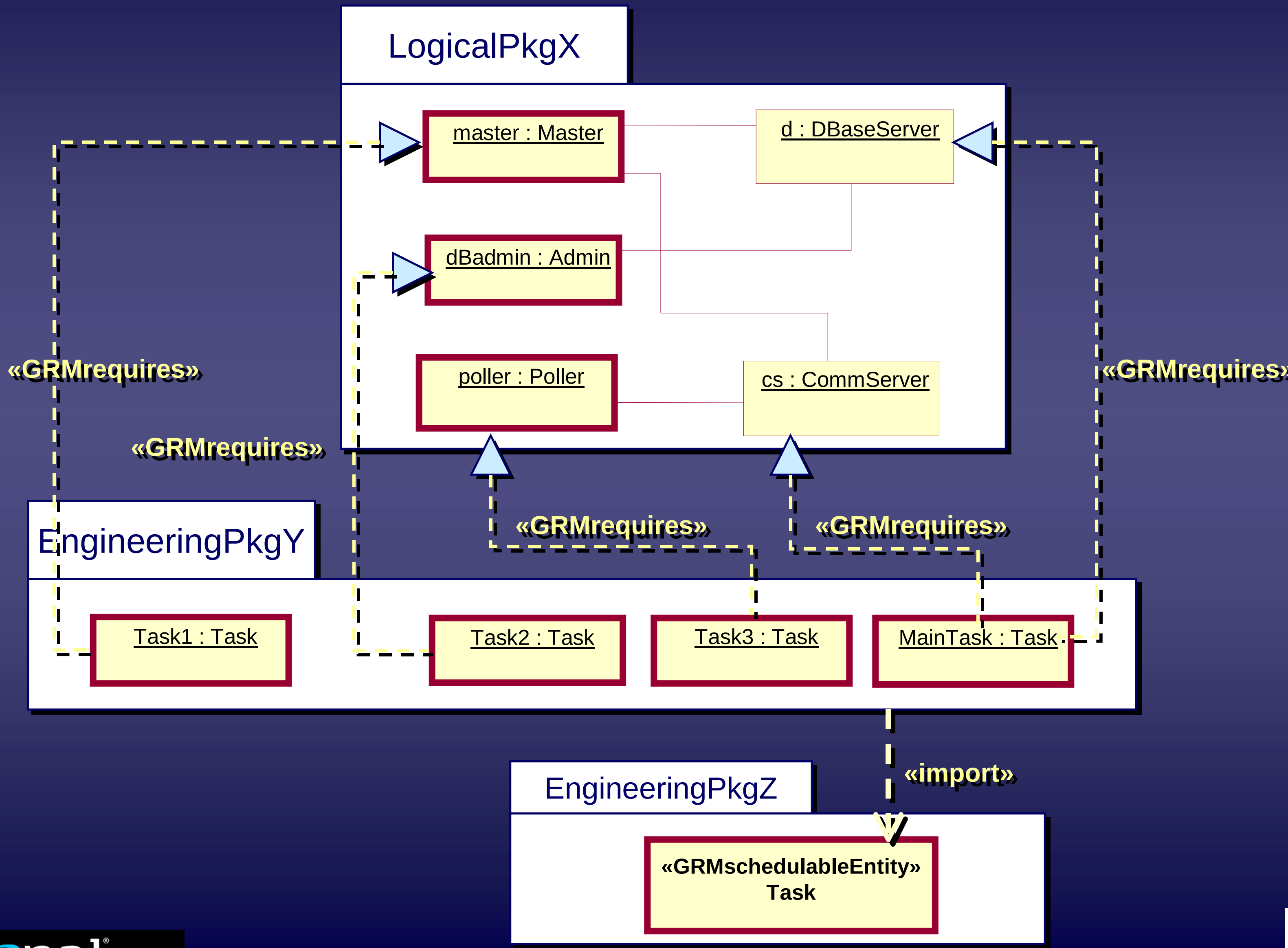
Stereotype	UML base concepts	Tags
GRMthreadEnv	Node, Instance	priority [0..1] : Integer heap [0..1] : Real stack [0..1] : Real

Example: Task Allocation

- The allocation of logical model to engineering model elements

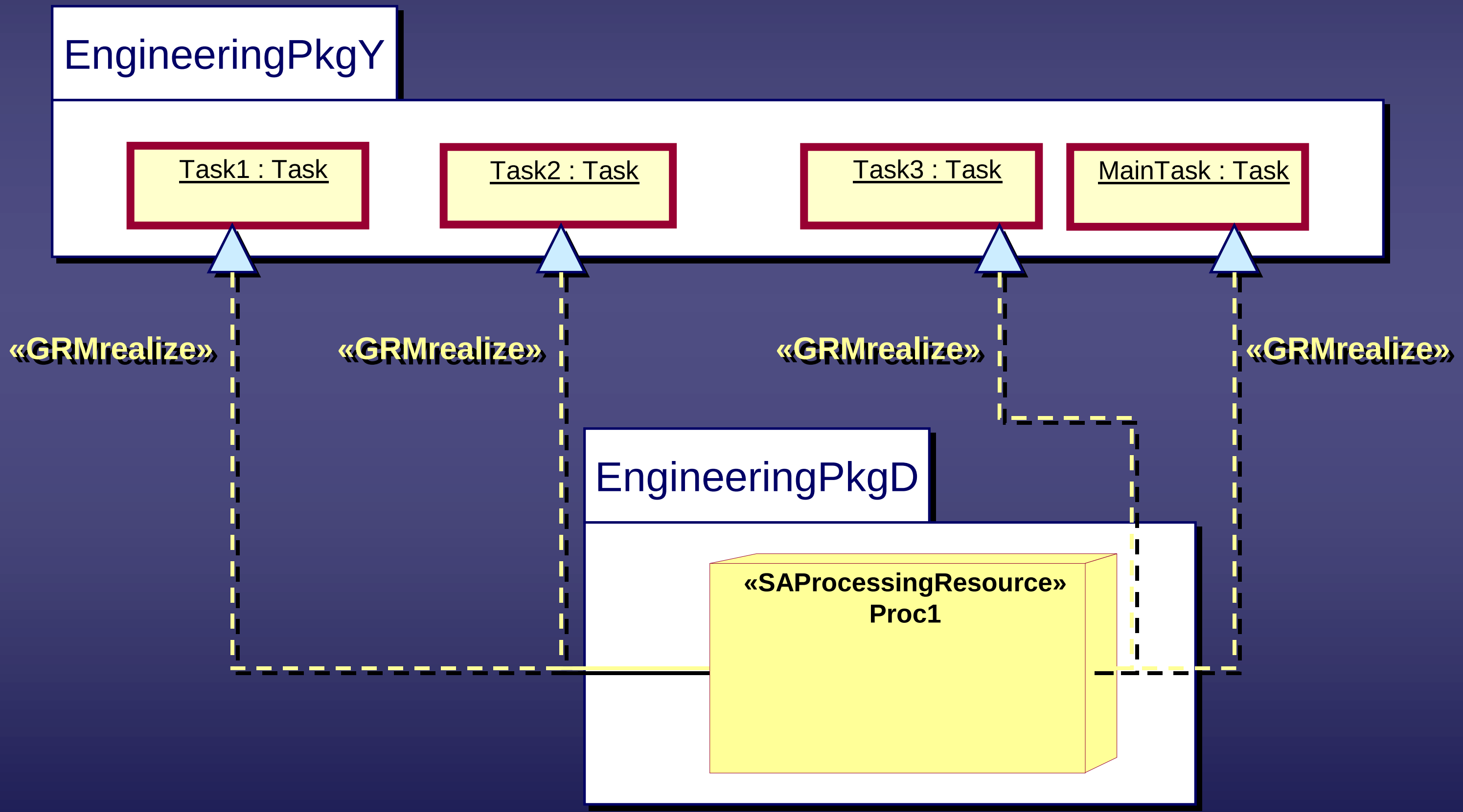


Example: UML Model of Allocation



Example: Completing the Mapping

- Mapping to hardware



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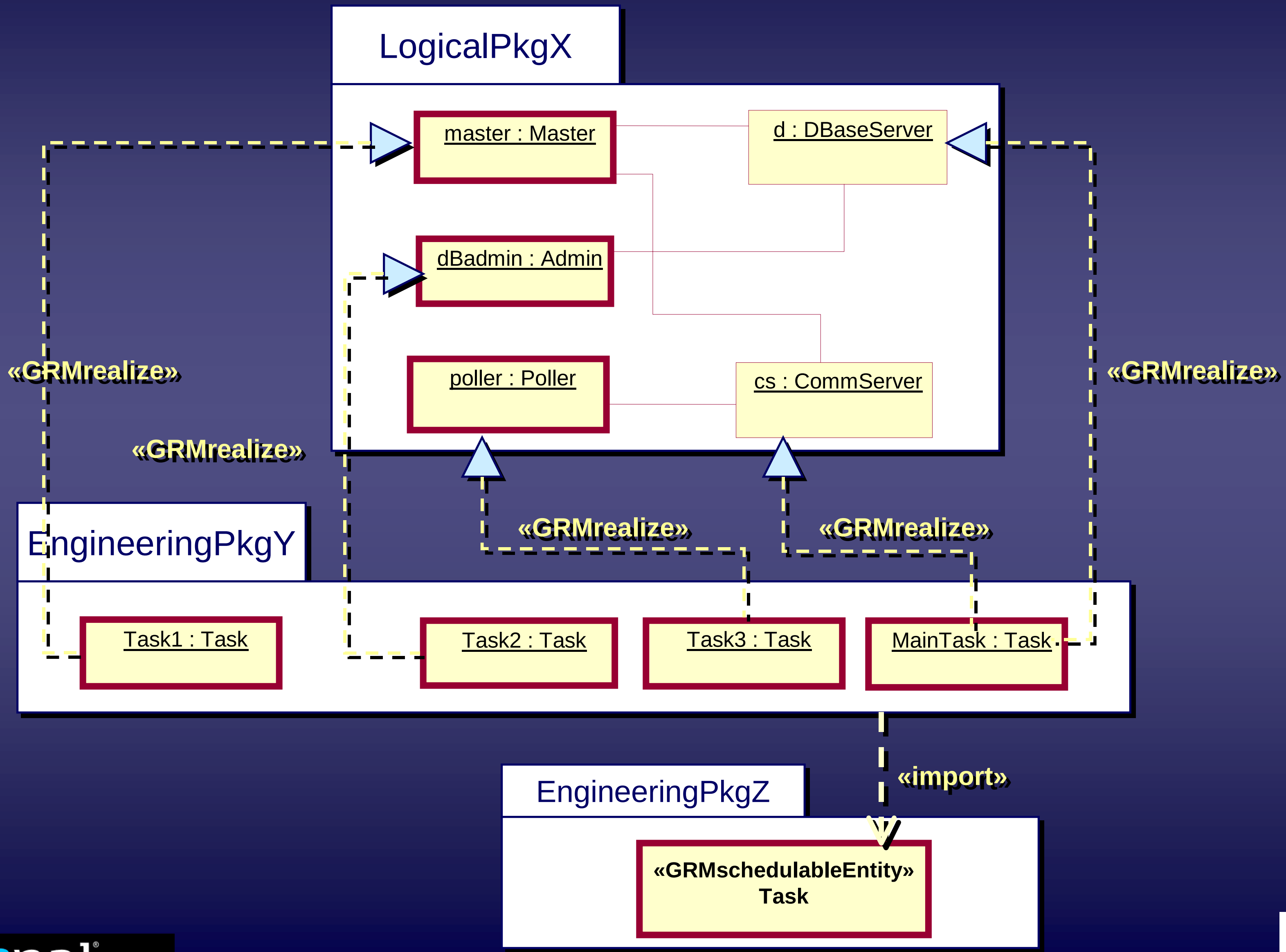

Example: Completing the Mapping

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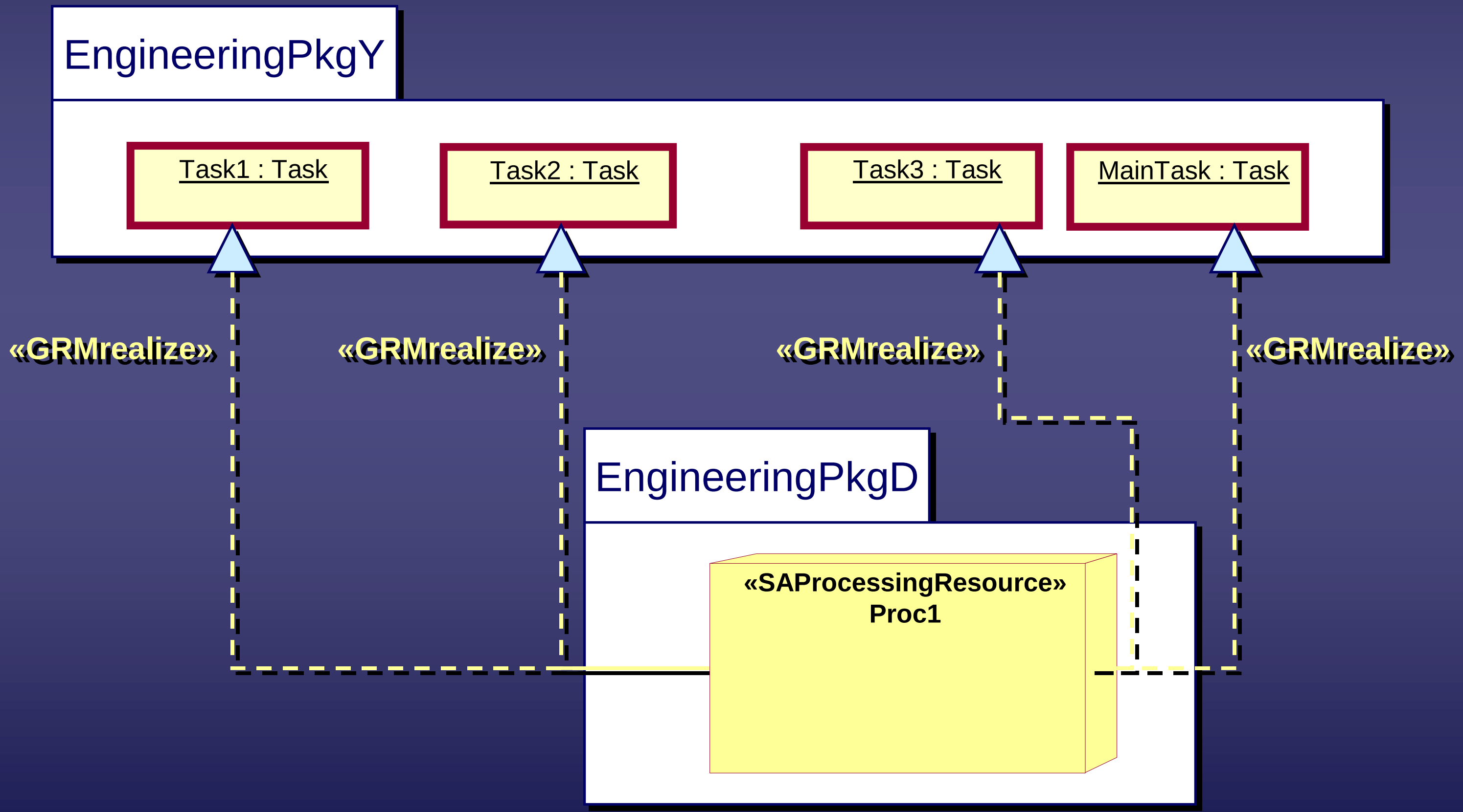

Summary: RT Design and Engineering

- 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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