Composing and Decomposing QoS Attributes for Distributed Systems:

Experience to Date and Hard Problems Going Forward

or How to Handle a 20 year problem in 2-3 year Increments

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and a host of talented colleagues, past and present

Monterey Workshop
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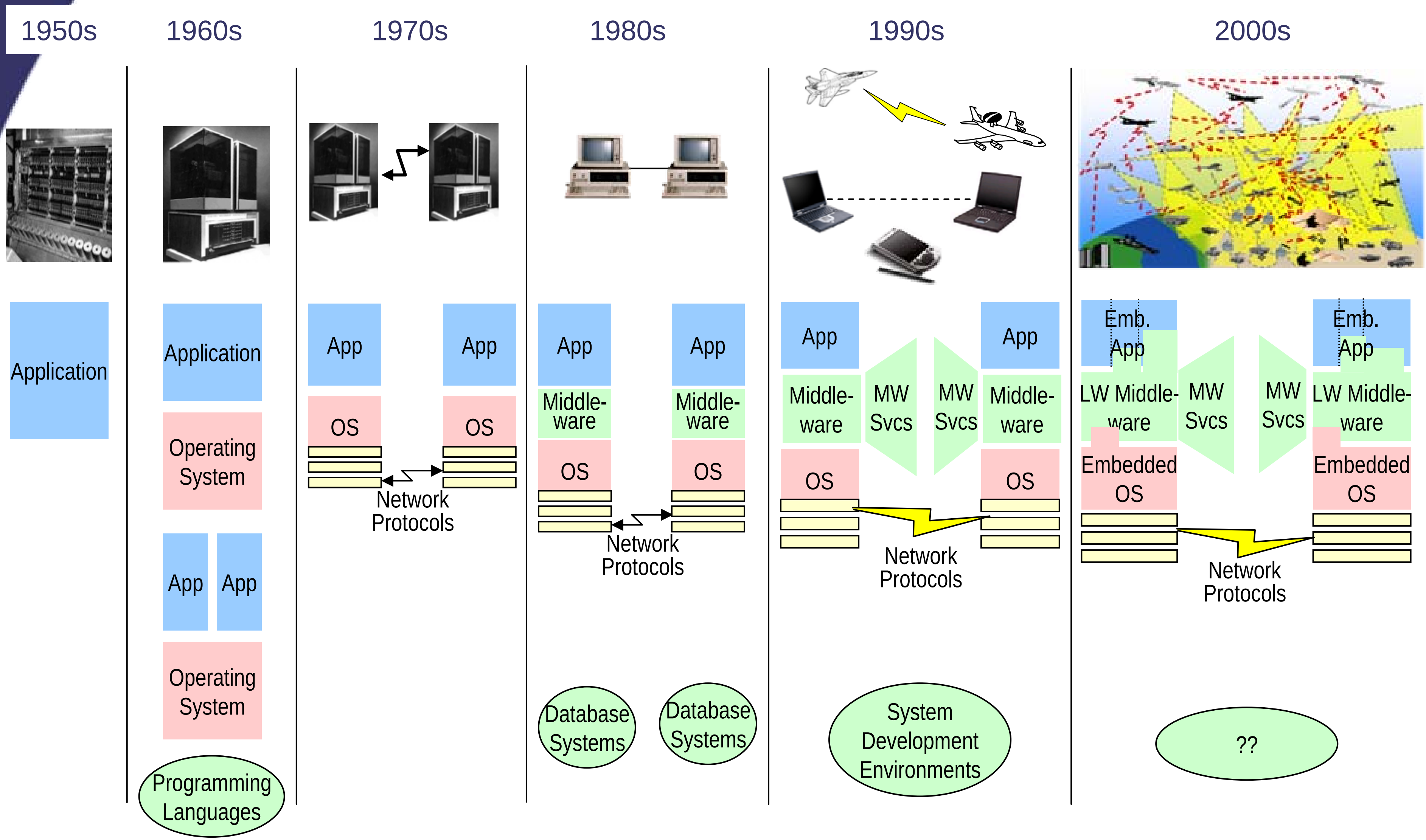
BBN TECHNOLOGIES

Brief Outline

- Context
- Examples
- Enabling Aspects, Building Blocks and Directions
- Hard Problems and Longer Range Issues, Looking Forward

Historical Context: Software Infrastructure Enables Application Capabilities



1950s **Fifty Years of Distributed Systems Software Architecture Evolution** 2006+

Background: Underlying Forces at Work

- Everything is a computer
- Everything is a networked computer
- Everything is potentially interdependent
- Things connect to the real physical world
- Increasing heterogeneity, distance and mobility

Mission critical distributed systems will continue to be built, fielded (and vulnerable) with or without proper basis, understanding and tools

Leading to Current Trends and Directions

- Need for Integrated/Managed End-to-End Behavior
  - Multi-dimensional
  - String & Aggregate
- Multi-Layered Architectures, Network-centric Services & Systems of Systems
- Adaptive Designs Over Widely Varying and Changing Configurations
  - Static → Dynamic
- (More) Advanced Software Engineering (trying to keep pace)
  - Methodologies, Processes, Tools, Complexity Management

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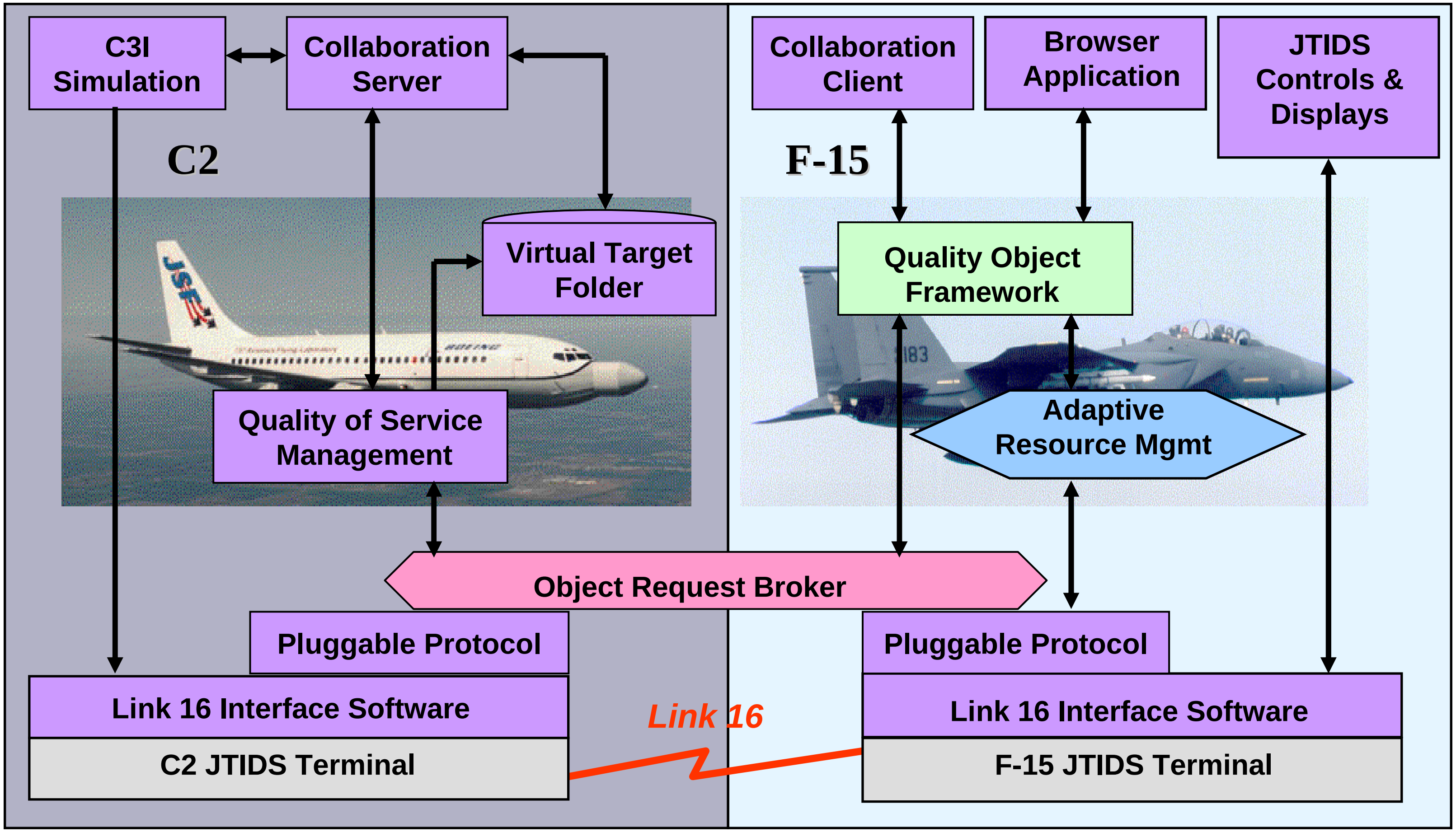
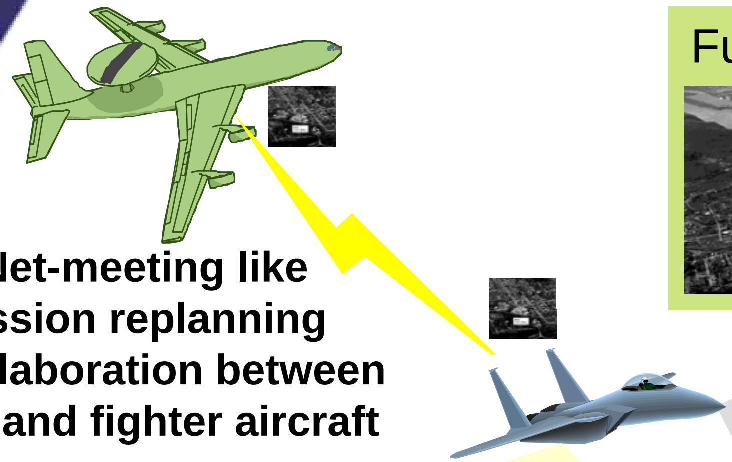
Avionics Dynamic Mission Planning

Example DRE Application 1



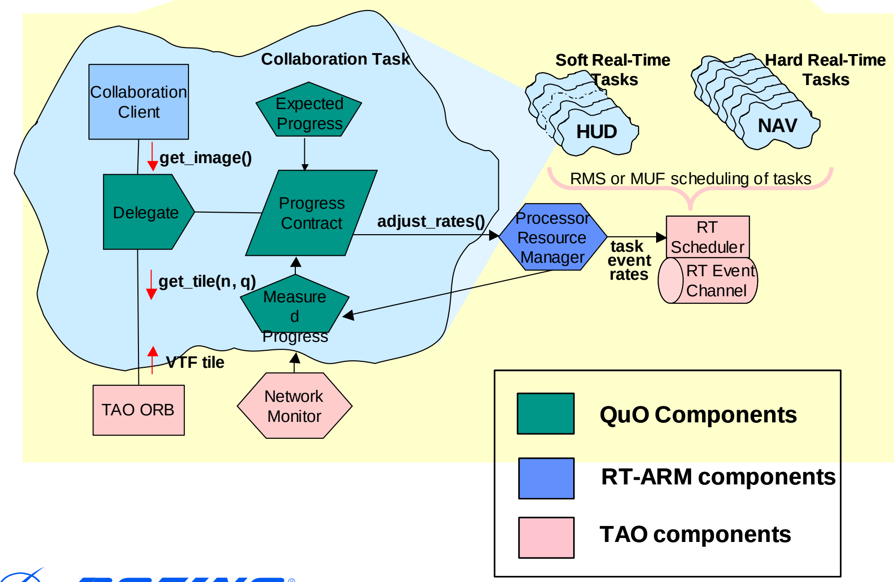
Avionics Dynamic Mission Planning

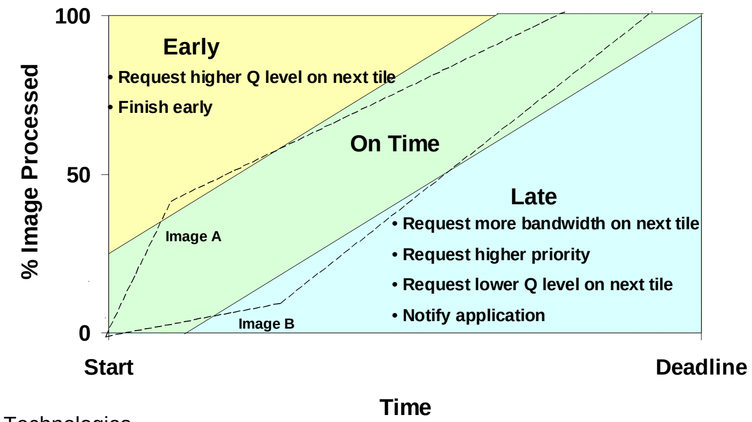


A Net-meeting like mission replanning collaboration between C2 and fighter aircraft

QoS Techniques

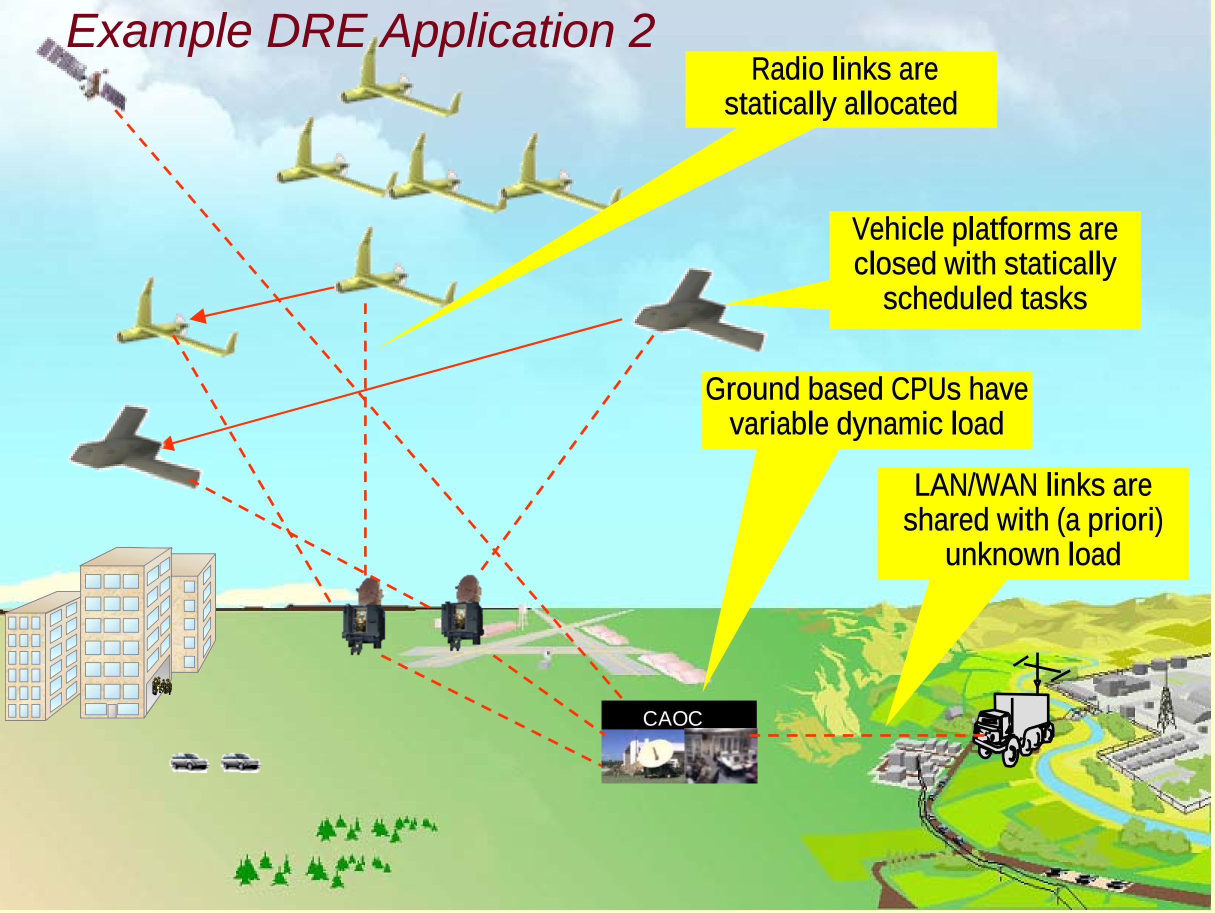
- Tiling
- Compression
- Processor Resource Management
- Network Resource Management





Multi-UAV Reconnaissance and Situation Monitoring Requires Dynamic End-to-End QoS Management

Example DRE Application 2



Heterogeneous, shared, and constrained resources

Multi-layer points of view: System-view, goal-view, application-string view, local resource view

Goal-defined requirements and tradeoffs (e.g., rate, image size, fidelity)

Changing modes, participants, and environmental conditions

End-to-End Objective-Driven QoS Management

Reconnaissance Mode

- Maximize area monitored
- Sufficient resolution in delivered imagery to determine items of interest

Situation Assessment

- UAV observing item of interest provides high resolution imagery so that unfolding situation can be monitored, assessed, and acted upon

After Action Assessment

- UAV provides high resolution imagery until a human operator has determined that it is sufficient
- UAV over item of interest must continue to provide situation assessment imagery

The challenge is to program the dynamic control and adaptation to manage and enforce end-to-end QoS.

Demonstration Imagery Displays (Simulated C2 Receivers)

Name, role and COI of the asset

Color of the border reflects the role of the SimUAV

Image size and rate are a result of QoS information management

QoS Policies Used in the Demonstration

Mission	Relative Priorities
ISR_COI	1
TST_COI	2

Qos Constraints and Tradeoffs

Roles	Relative Priority	Resource Needed			Quality of Information Needed			
		BW Needed (kbps) (Min-Max)	DiffServ Codepoint	CPU (Receiver) (%)	Rate (Timeliness) IO/Frame Rate	Scaling (Size)	Compression (Accuracy)	Cropping (Precision)
SURVEILLANCE (ISR)	1	50-200	Best Effort	0.1-2.0	0.1 – 0.4	Qtr-Qtr	JPG-JPG	None
TARGET TRACKING (TT)	6	150-600	Expedited Forwarding	1.5-5.5	1-1.5	Half-Half	None - JPG	None
BATTLE DAMAGE ASSESSMENT (BDA)	4	300-400	Assured Forwarding	1.5-3.0	0.25-0.5	Full-Full	None-JPG	None-30%

"Defense Enabling" Distributed Applications
The DPASA Project

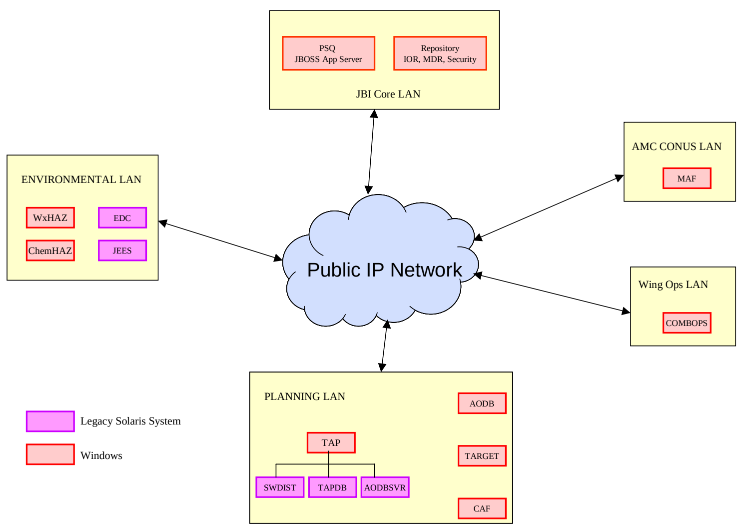
Example DRE Application 3

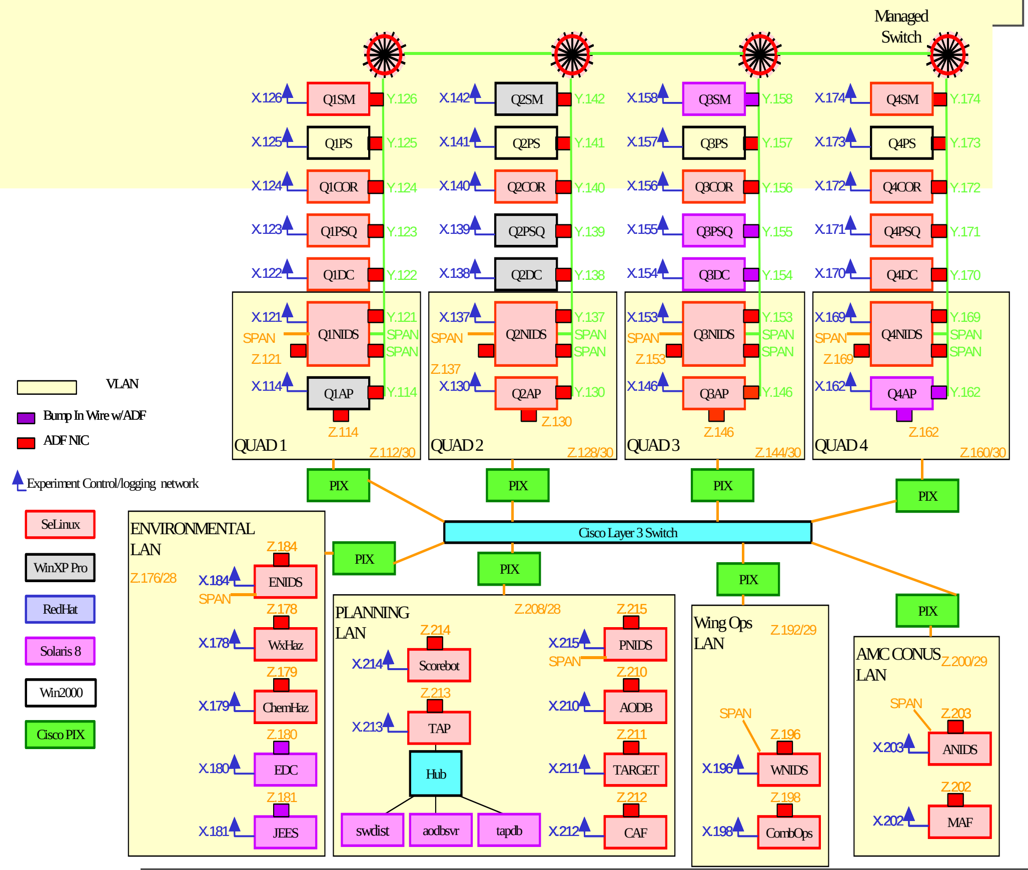
Build an information management system that can survive sustained attacks from nation-state adversary and complete its mission

Operate through attacks by using a layered defense-in-depth concept

- Accept some degradation
- Protect most valuable assets
- Move faster than the intruder

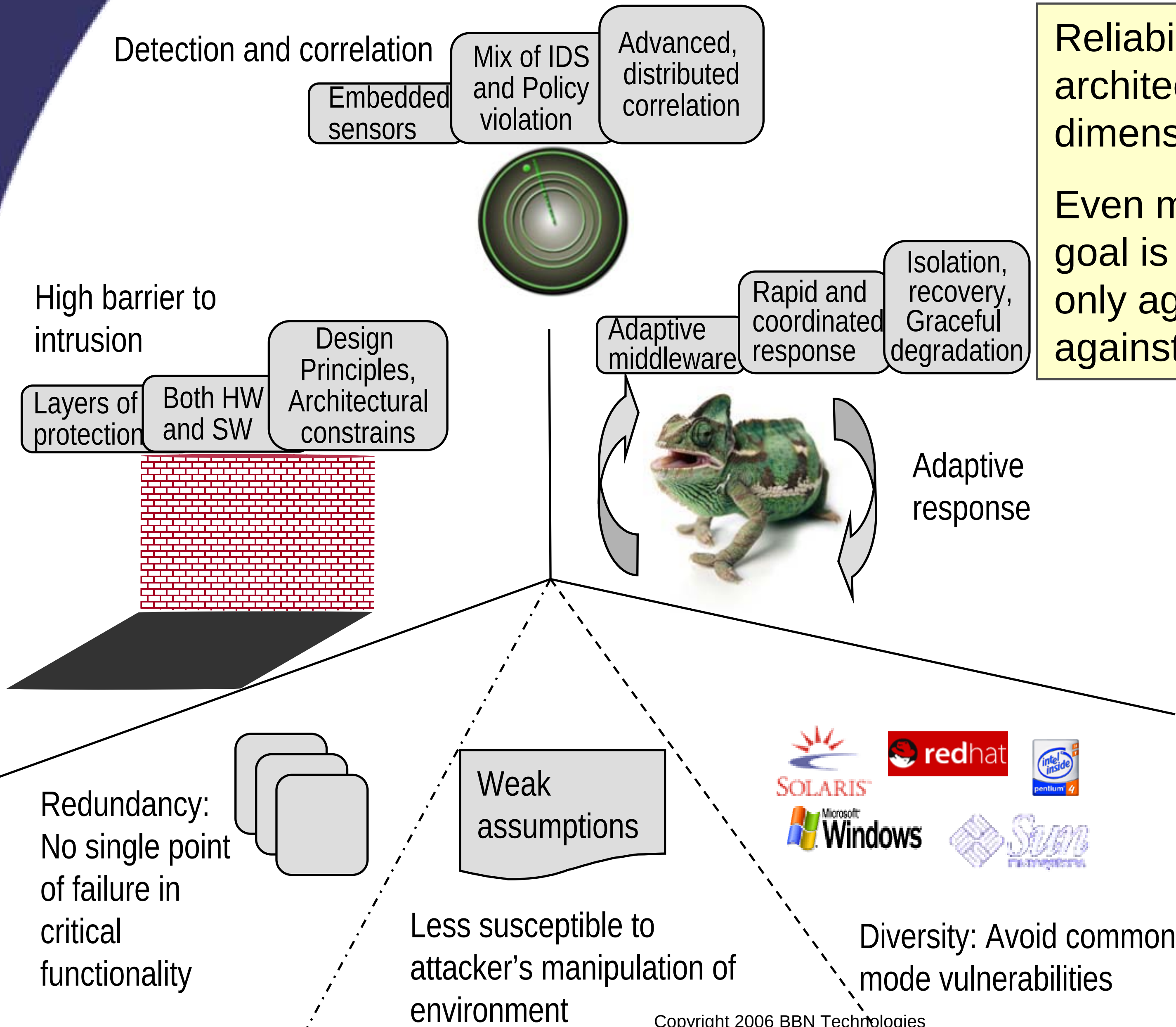
Notional diagram of the undefended system





Defense-enabled system

Architecting Survivability into Large Systems With Realtime Response



Reliability requires architecting in multiple dimensions

Even more so, when the goal is to be resilient not only against errors, but also against attacks….

General principles for survivability

- Protect as best as possible
- Improve chances of detection
- Adapt to manage gaps

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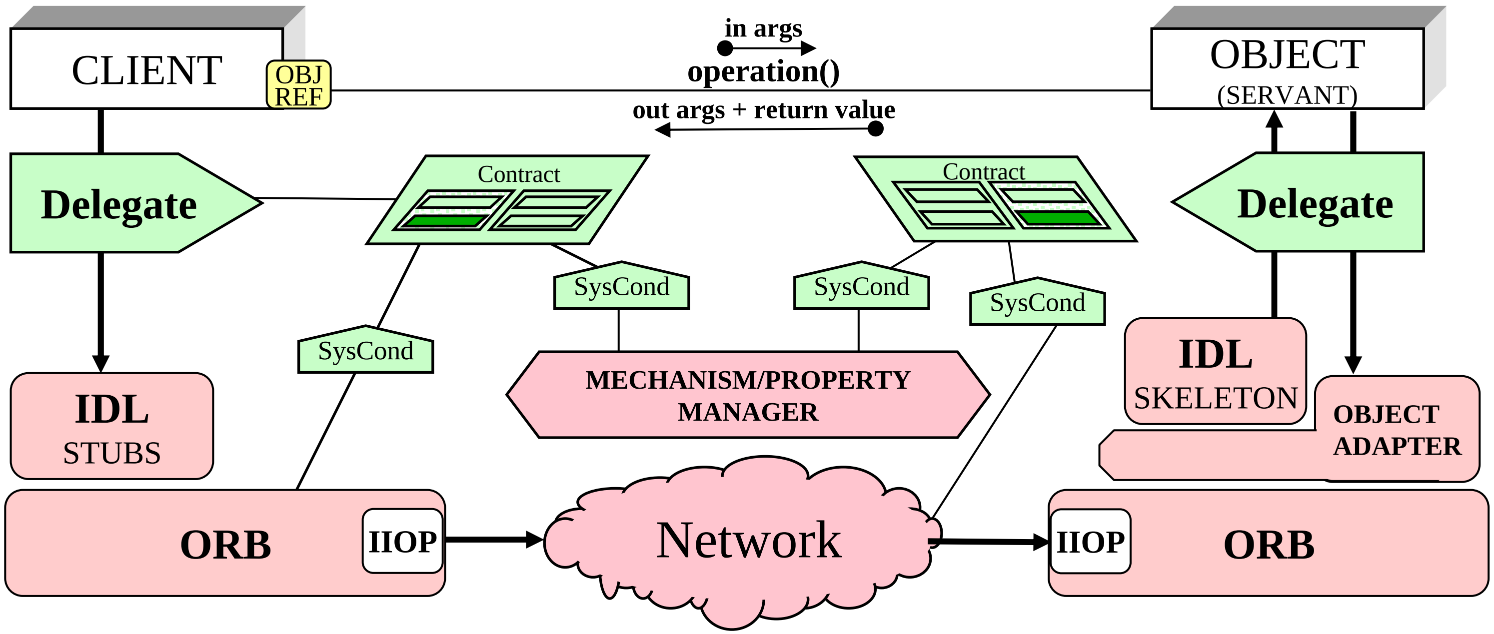
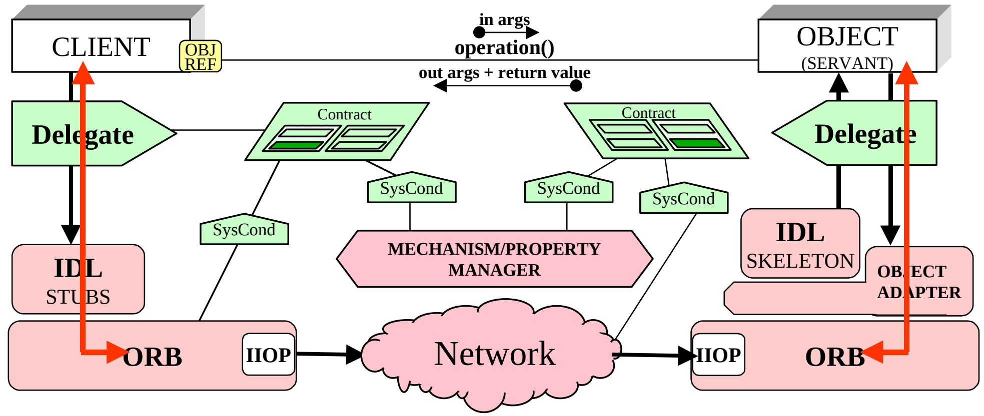
A Minimum Set of Capabilities for QoS Adaptive Middleware

- *Specify* the QoS needs of a mission, application, system
- *Measure* the QoS available in a system
- *Control* knobs to achieve QoS
- *Adapt* to compensate for changes in QoS
- *Mediate* conflicting QoS requirements

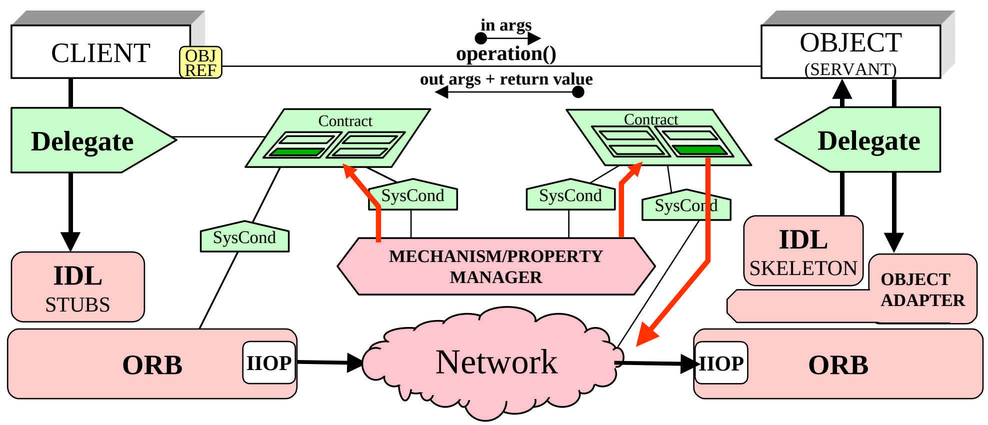
Adaptive Behavior Enablers



Use Cases



CLIENT
OBJ REF
in args
operation()
out args + return value
OBJECT
(SERVANT)
Delegate
Contract
Contract
Delegate
SysCond
SysCond
SysCond
SysCond
IDL
SKELETON
MECHANISM/PROPERTY MANAGER
IDL
STUBS
OBJECT ADAPTER
ORB
IIOP
Network
IIOP
ORB



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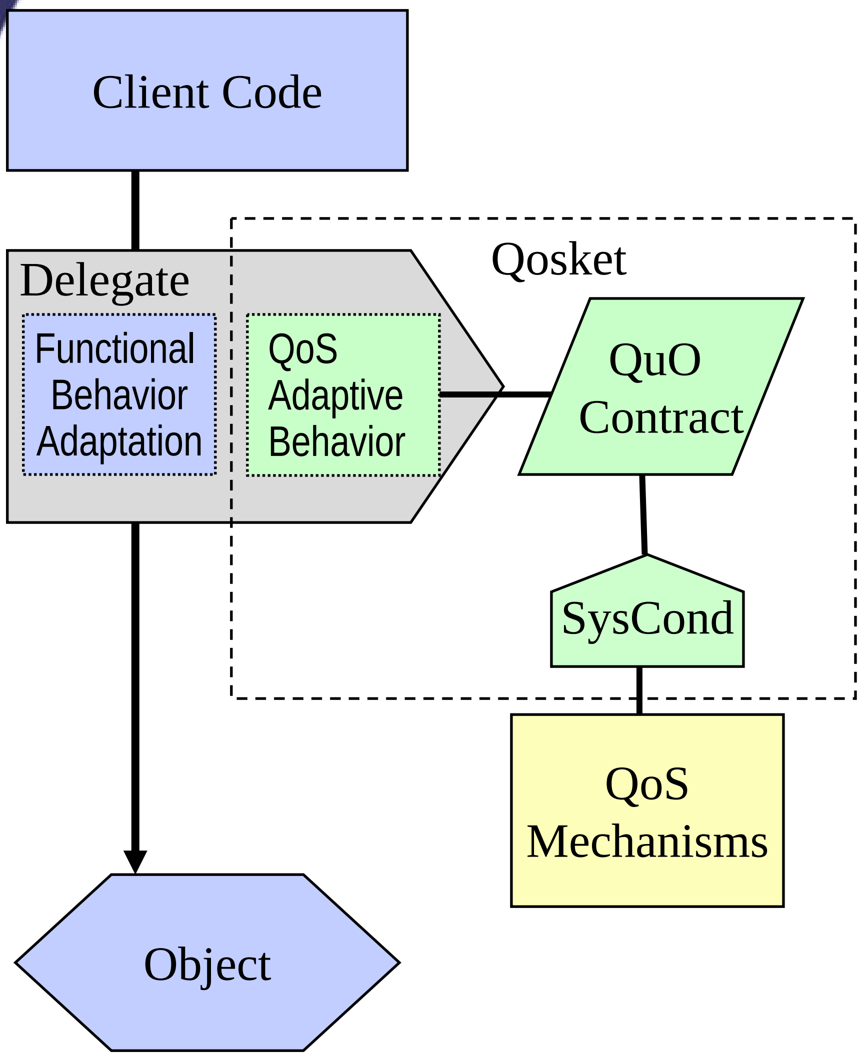
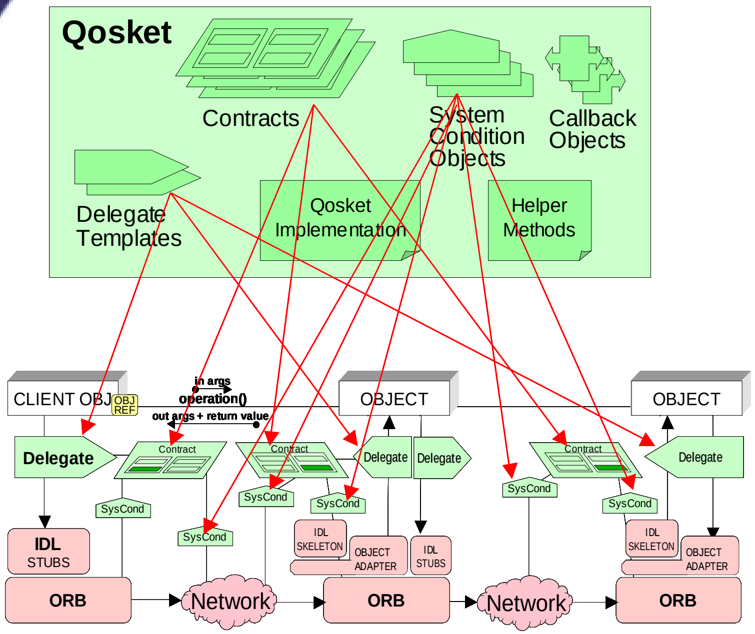
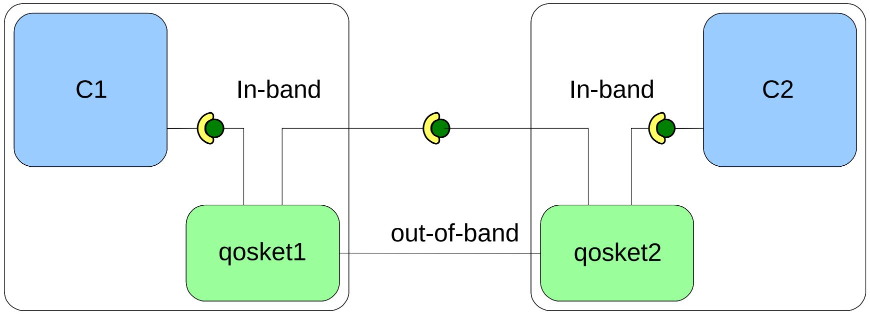
QuO Components Are Packaged into Reusable Bundles of "Systemic Behavior" Called Qoskets



- The Qosket encapsulates a set of contracts (CDL), system condition objects (IDL), and QoS adaptive behavior (ASL)
- The Qosket exposes interfaces to access QuO controls and information (specified in IDL)
- The Qosket separates the functional adaptive behavior (business logic) from the QoS adaptive behavior and the middleware controls from the QoS mechanisms

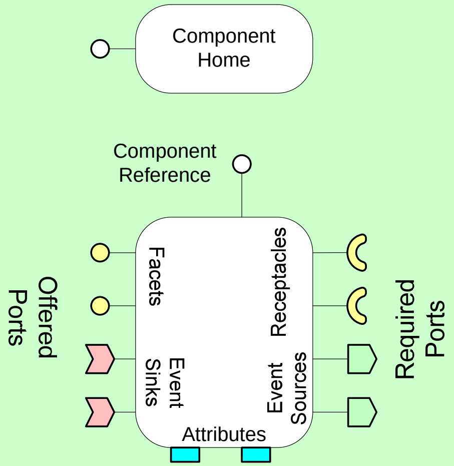
Component-Based Adaptive QoS Frameworks





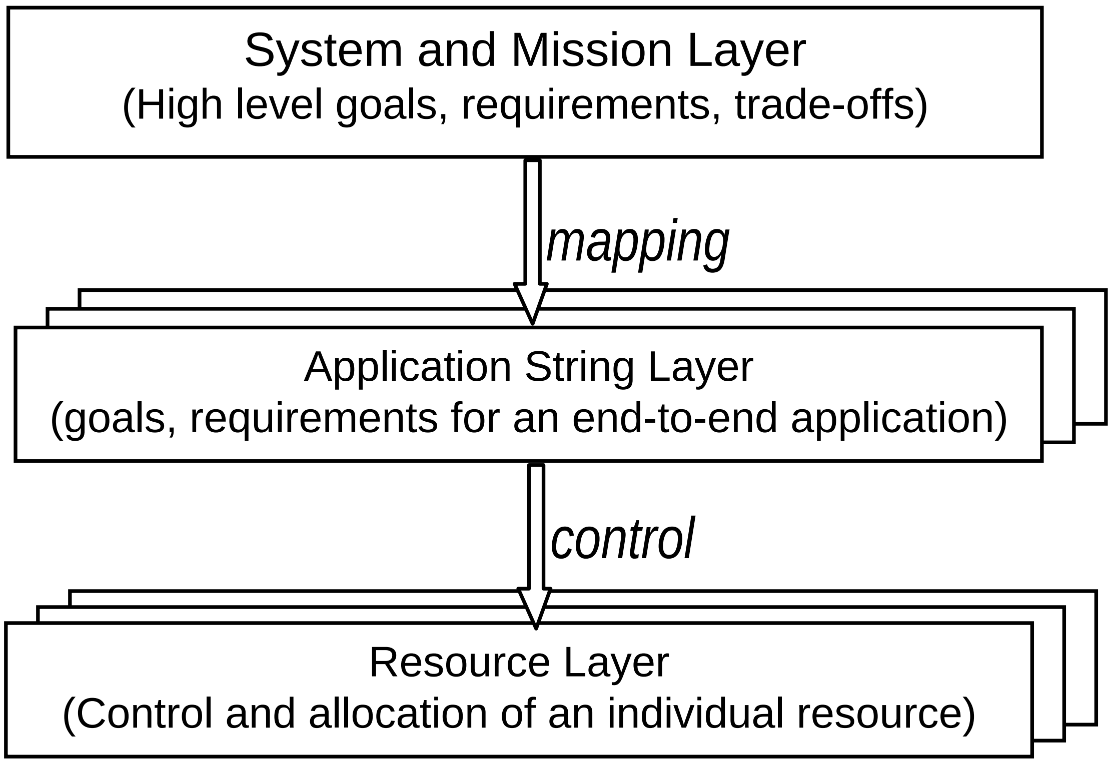
- Complementary CCM and Qosket ideas
  - CIAO, Prism support static QoS
  - Qoskets support dynamic, adaptive QoS
- Lifecycle support for dynamic QoS
  - Information available at design, configuration, assembly, and run times
- Crosscutting QoS concerns become many distributed qosket components
  - Better assembly and transparency using CCM tools
  - QoS policies in components, containers, and ORBs working with dynamic contract-based QoS and resource management

CORBA CCM

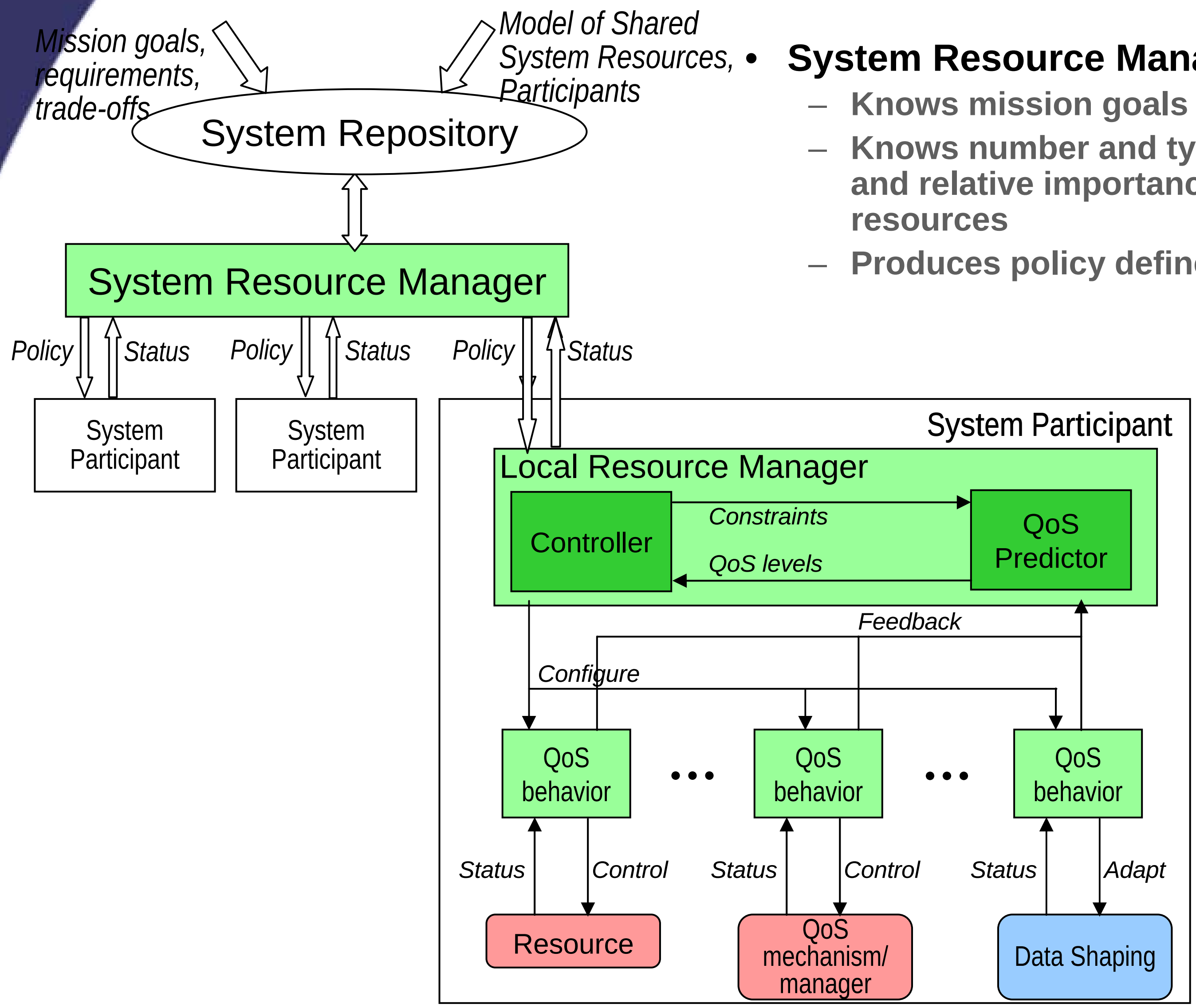


- Component frameworks need static and dynamic QoS management to be suitable for DRE environments
- QoS encapsulation (e.g., *qoskets*) within a component framework (e.g., *CCM*) offers the potential for improved composition, transparency, and lifecycle support for QoS

Multi-Layer QoS Management Architecture



Multi-Layer QoS Management Design



- **System Resource Manager (SRM)**
  - Knows mission goals and tradeoffs
  - Knows number and types of participants, roles and relative importance, and available shared resources
  - Produces policy defined for each participant
- **Local Resource Manager (LRM)**
  - Determines how to utilize allocated resources to meet mission goals
  - Configures and monitors QoS behaviors to enforce QoS policy
- **QoS behaviors**
  - Control and monitor individual resources or mechanisms, or adapt individual behavior

Algorithms

One prototype algorithm:

First compute an allocation unit

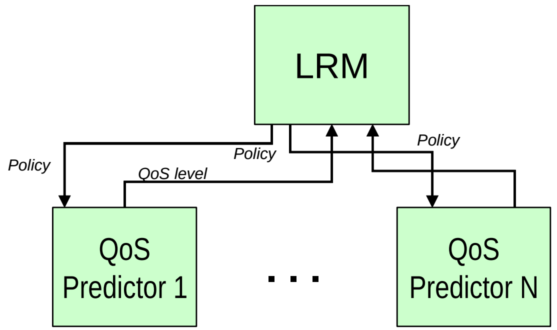
$$alloc\_unit = \frac{(resources\ available)}{\left(\sum_{i\in roles}(number\ of\ assets\ in\ role\ i)\times(weight\ of\ role\ i)\right)\left(\sum_{j\in COIs}(weight\ of\ COI\ j)\right)}$$

Next, allocate each asset a number of *allocation units* sufficient to satisfy its roles and the COIs it participates in

$$allocation_{asset\,k} = alloc\_unit \times \left(\sum_{i\in roles} asset_k\ in\ role\ i \Rightarrow weight\ of\ role\ i\right)\times\left(\sum_{j\in COIs} asset_k\ in\ COI\ j \Rightarrow weight\ of\ COI\ j\right)$$

But not less than its minimum or more than its maximum

Resource Allocation Algorithm



QoS Enforcement Algorithms

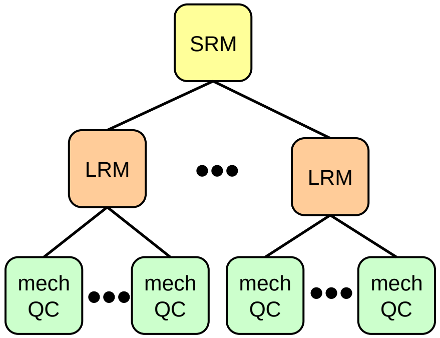
Resource Allocation Algorithms

- We prototyped a few (variations) allocating based on priority, role, weight, number of assets, and available resources
- The current algorithm allocates one resource at a time
- Still some hard problems in allocating for more than one resource at a time
  - Multi-dimensional resource provisioning
  - Capturing *system dynamics* (how changes in one part of the system affects other parts)
  - Measures of utility to drive resource allocation

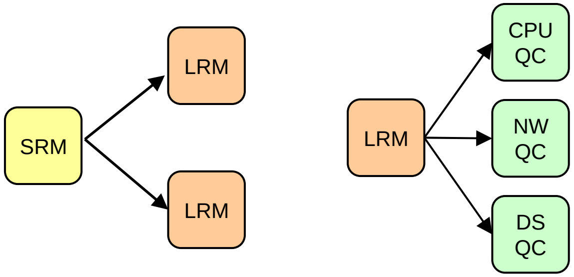
QoS Enforcement Algorithms

- We prototyped QoS predictor and mechanism algorithms for a few resources (e.g., bandwidth), datatypes (e.g., images), and techniques (e.g., pacing, compression, scaling)

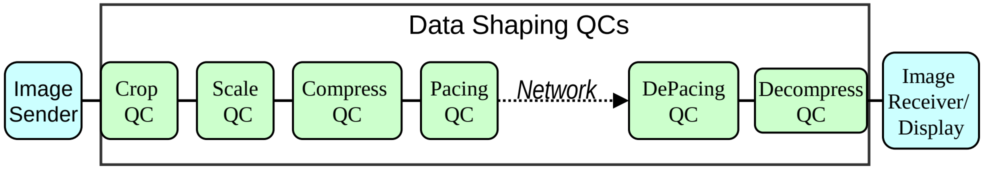
Patterns of Component Composition



Hierarchical



Parallel



Sequential

Multi-Layered End-to-End QoS Management

End-to-end QoS management **must**

- Manage all the resources that can affect QoS, i.e., anything that could be a bottleneck at any time during the operation of the system (e.g., CPU, bandwidth, memory, power, sensors, …)
- Shape the data and processing to fit the available resources and the mission needs
  - What can be delivered/processed
  - What is important to deliver/process
- Includes capturing mission requirements, monitoring resource usage, controlling resource knobs, and runtime reallocation/adaptation

Control and Monitor Network Bandwidth

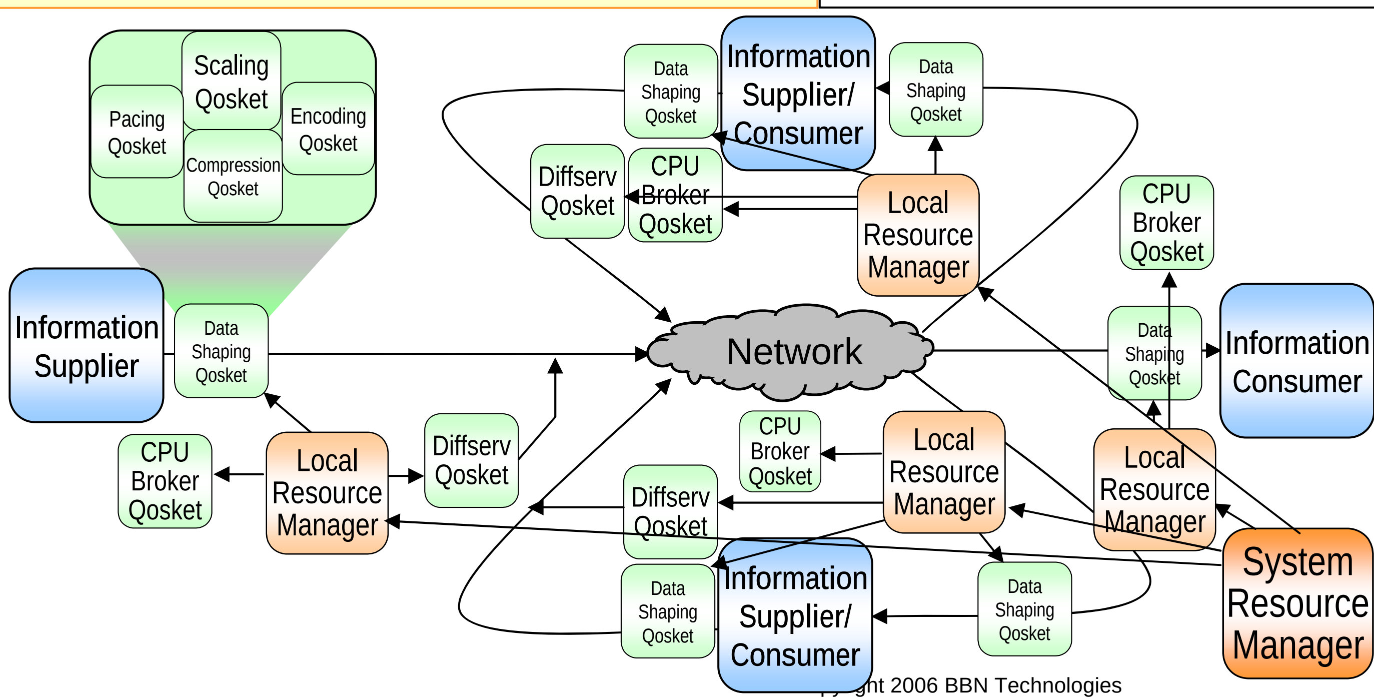
- Set DiffServ CodePoints (per ORB, component server, thread, stream, or message)
- Work with DSCP directly or with higher level bandwidth brokers
- Priority-based (Diffserv) or reservation-based (RSVP)

Control and Monitor CPU Processing

- CPU Reservation or CPU priority and scheduling
- Have versions that work with CPU broker, RT CORBA, RTARM

Shape and Monitor Data and Application Behavior

- Shape the data to fit the resources and the requirements
- Insert using components, objects, wrappers, aspect weaving, or intercepters
- Library that includes scaling, compression, fragmentation, tiling, pacing, cropping, format change



Coordinated QoS Management

System resource managers allocate available resources based on mission requirements, participants, roles, and priorities

Local resource managers decide how best to utilize the resource allocation to meet mission requirements

Dynamic QoS realized by
- Assembly of QoS components
- Paths through QoS components
- Parameterization of QoS components
- Adaptive algorithms in QoS components

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Integrating the Components

End-to-End Quality of Service

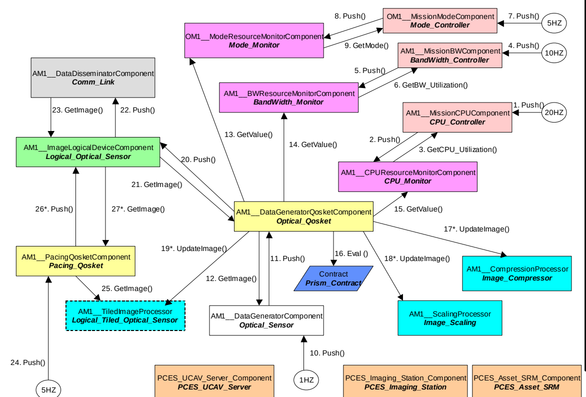
Local resource manager configures qoskets to enforce resource management

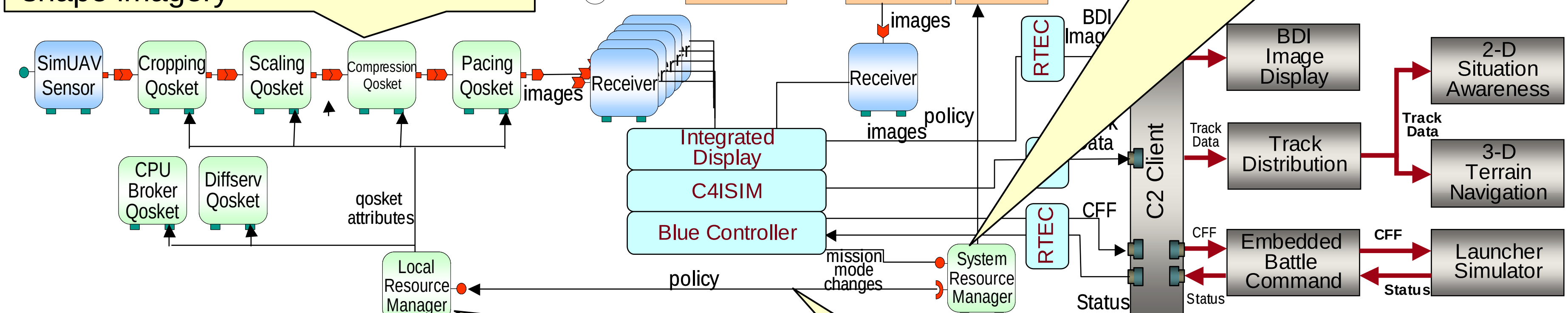
- Diffserv Code Point
- CPU reservation
- Rate, compression level, amount to scale or crop

Qoskets control resources and shape imagery

System resource manager determines allocation of resources to participants and roles

- Assigns a weight to each role based on its relative importance (from the blue controller)
- Divides the total amount of resources (e.g., Mbps or %CPU) by the number of participants in all roles multiplied by their weight to get a resource unit
- Each participant is allocated a resource unit times the weight of its role





Local resource manager determines how best to utilize allocated resources

- Diffserv Code Point (based on relative importance of role)
- CPU reservation
- Shaping data to fit allocated CPU and bandwidth: rate, size (cropping or scale), compression
- Chooses based on resource allocation and mission needs of the role

System resource manager pushes policy to each participant (SimUAVs)

- Role
- Relative importance
- Resource allocation
- Min and Max allowed (from mission requirements)

Dynamic Reconfiguration

Mission Mode Changes and Reconfiguration
Dynamic End-to-End QoS Management

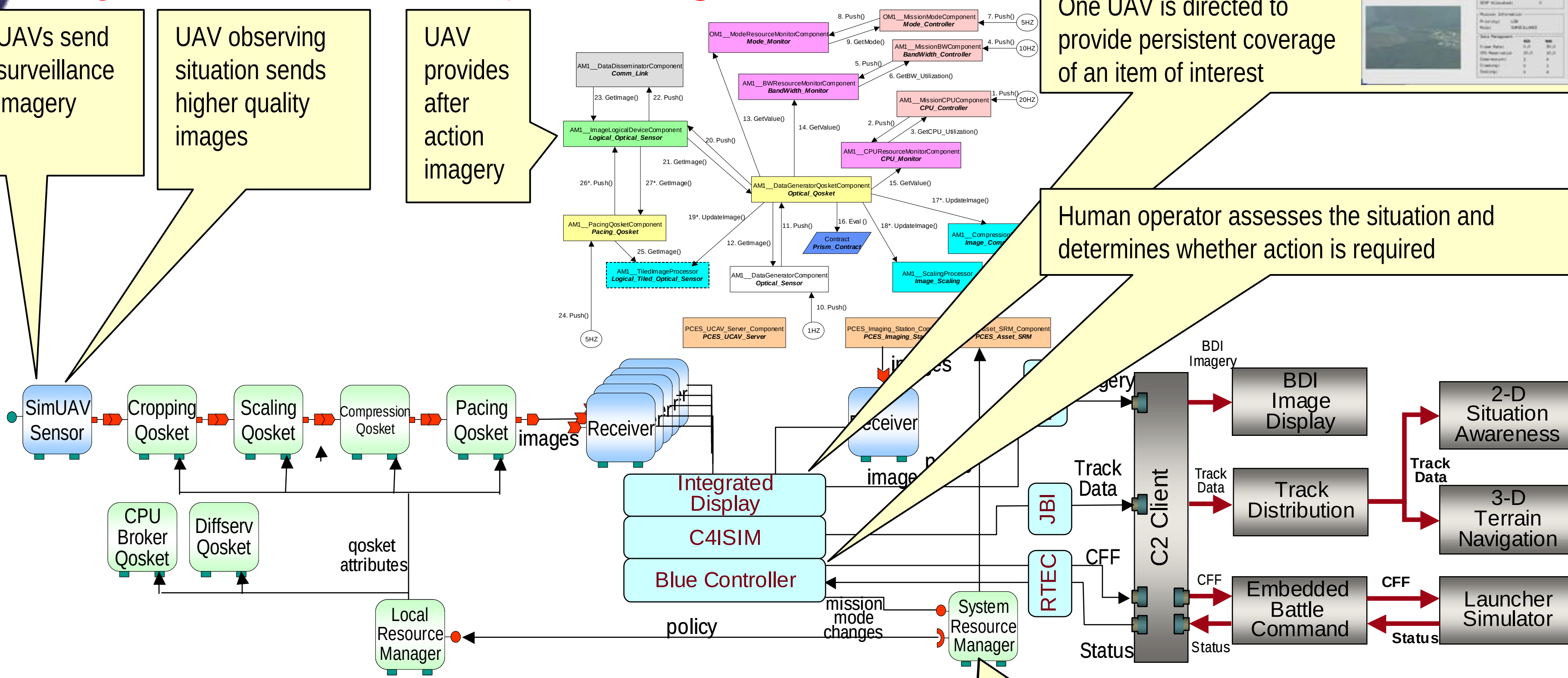
UAVs send surveillance imagery

UAV observing situation sends higher quality images

UAV provides after action imagery

Surveillance imagery is displayed at ground display; One UAV is directed to provide persistent coverage of an item of interest

Human operator assesses the situation and determines whether action is required



SRM reallocates resources and pushes new policy to participants; LRM determines new adaptation and control.

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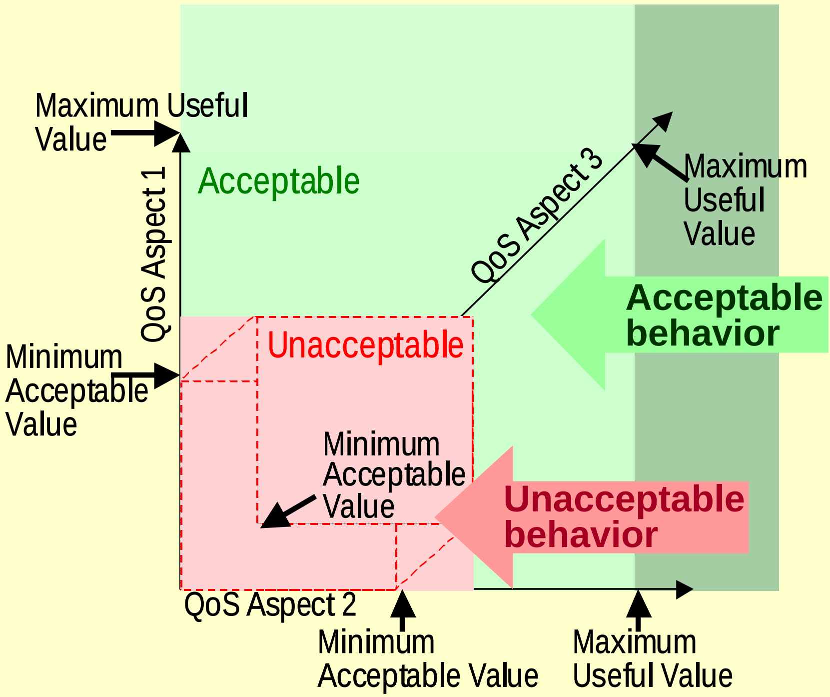
Looking Forward Again: Three Areas of Continued R&D

1. Heterogeneity is your friend, but is still too costly
   - On the one hand we often preach it,
   - But in practice we avoid it
   - Needs fixing, to avoid the risks of innovation slowdown & monoculture

2. Lot's and lot's of interacting pieces across platforms with realtime requirements over shared environments
   - Mandates new higher level abstractions for development and tools, tools, tools

3. Many of the distributed, realtime, embedded environments we engage have certifiability requirements
   - Current approach is completely static and exhaustive testing
   - Interconnection drives dynamic behavior which breaks current approaches

Moving To A Higher Level of Abstraction – Model Based Design of Runtime Adaptive Behavior

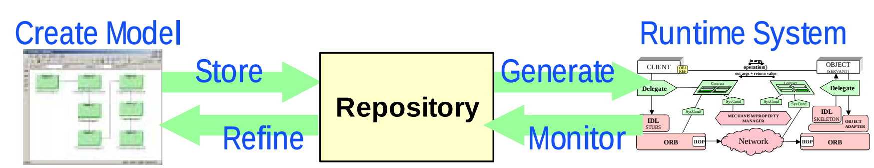


Modeling of QoS for DRE adaptive applications that behave appropriately under dynamic conditions

- Simplify the development of end-to-end and system-wide QoS adaptation and control for DRE systems
- Enable a larger class of practitioners, i.e., adaptive DRE system builders with less training in QoS or adaptive programming
- Improve the formalization, robustness, and usability of QoS adaptive concepts and applications.

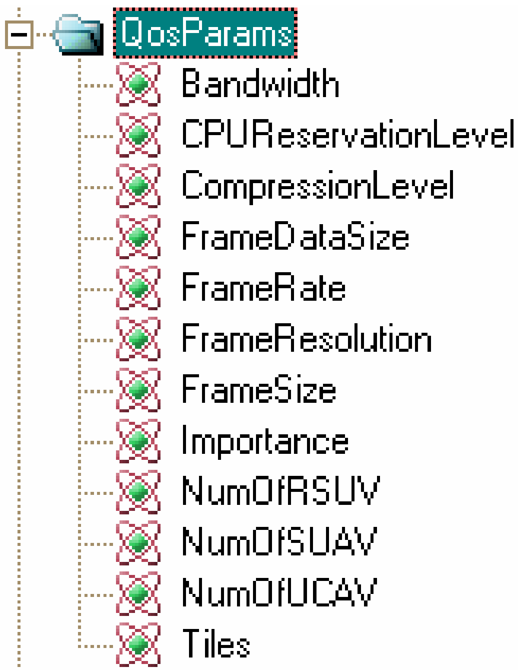
Want to model and synthesize adaptive behaviors that

- Ensure predictable, controlled behavior
- Satisfy mission requirements (i.e., use requirements to choose suitable tradeoffs)
- Gracefully degrade and recover



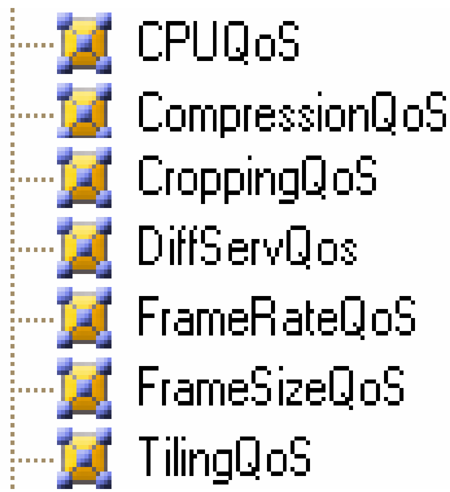
Observable and Controllable Parameters and Adaptation Behaviors

Observable and Controllable Parameters



Adaptation Behaviors

We have a set of off the shelf encapsulated behaviors (*qoskets*)



- CPU Broker
- Compression
  - Wavelet, JPEG, PNG
- Cropping
- Setting Diffserv Codepoints
- Pacing (changing frame rate)
- Scaling
- Tiling

Two levels of resource management controllers

- A *system resource manager* that sets policy for participants
- *Local resource managers* that enforce policy

Adaptive Distributed Systems and Certification

- Adaptive Systems reallocate resources and change strategies at run-time
- provide system agility to tolerate
  - Failures, changing workloads, etc.
- tailors allocations and strategies to current conditions
- cannot deploy adaptive systems unless certified
- static approaches are generally not feasible
  - cannot always know worst-case
  - allocation is not fixed
  - too many choices and possibilities to analyze statically and to largely rely on testing
- need some new approaches to certification

Investigating Ideas Toward the Certification of Dynamic Systems

- To facilitate certification, the process of creating dynamic systems needs to include two related pieces
  - The **ability to *assess*** the comprehensive quality, reliability, and correctness of system behavior
  - The **ability to (**positively and assuredly) ***control*** system behavior
- These two go hand-in-hand for certification
  - Ability to drive the system toward assessable "good" behavior
  - Ability to prevent the system from incorrect, unreliable or "bad" behavior
- These two together can potentially provide **a basis for *evidence-based certification***

Utility-Based Certification

- Utility measures can capture attributes of system performance and quality
  - Measure user-perceived value derived from control
  - Provide **a quantitative measure for certification**
- Considering Utility as measured and computed at each level of abstraction

System utility: $$U = \sum_{i=0}^{M} w_i^m U_i^m$$

Mission utility: $$U_i^m = \sum_{j=0}^{S_i} w_i^{S_j} U_i^{S_j}$$

String utility: $$U_i^{S_j} = \frac{1}{P_j} \sum_{i=1}^{P_j} u_l^{job}$$

Job utility involves combinations of continuing service and meeting deadlines, …

- Feedback control uses utility measurements/estimates to drive toward higher (increasing) utility
  - Allows system to dynamically respond to unforeseen situations