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Multiple Views on Multiplicity Computing:
Opportunities Viewed through a Cyber-Security Lens

CREST Workshop

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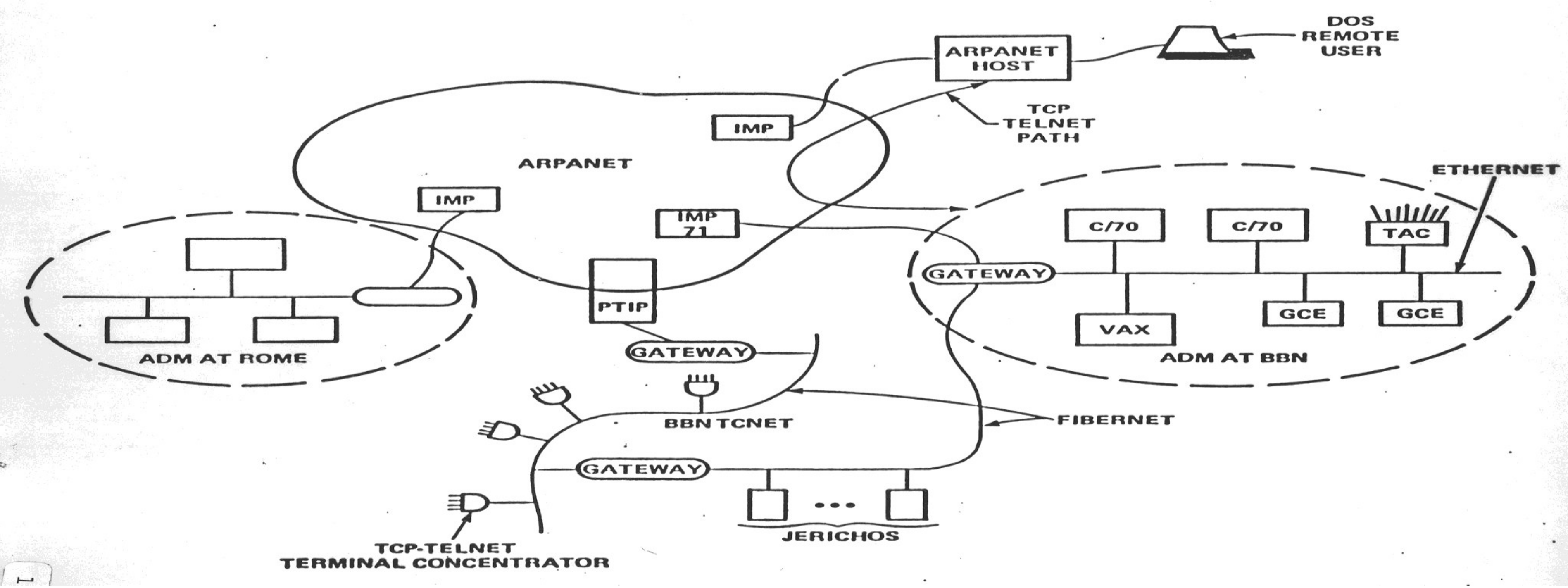
1982: R&D Computing Landscape



Multiplicity emerging …

1982: Heterogeneity, Specialization Among Plenty (or so it seemed at the time)

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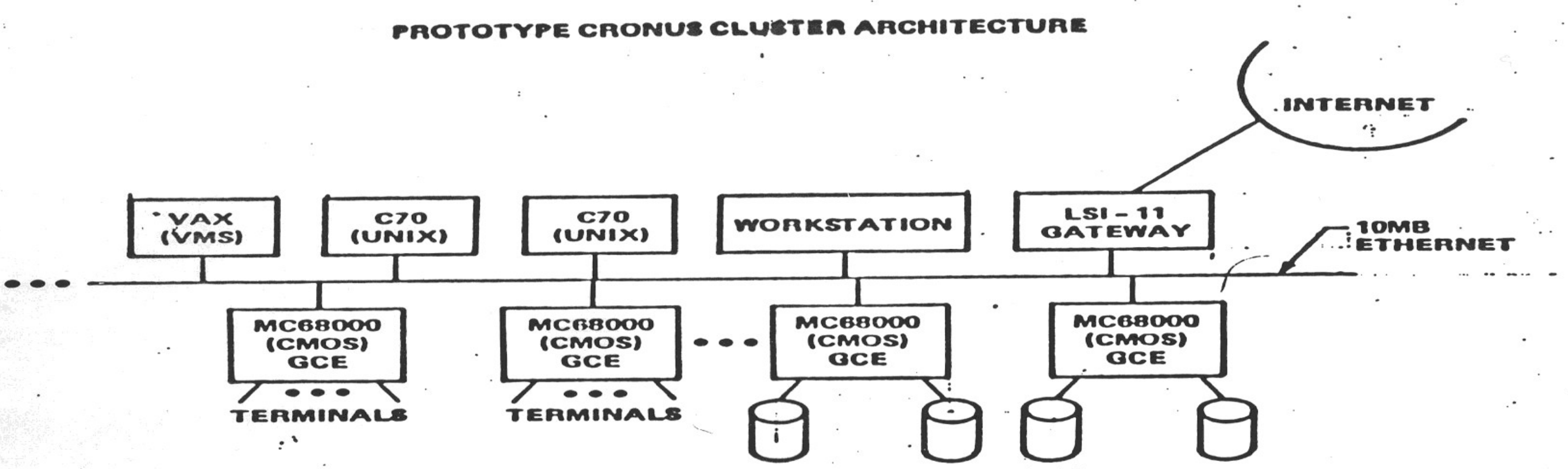

1990s Integrated Adaptive System Concept

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System-wide QoS

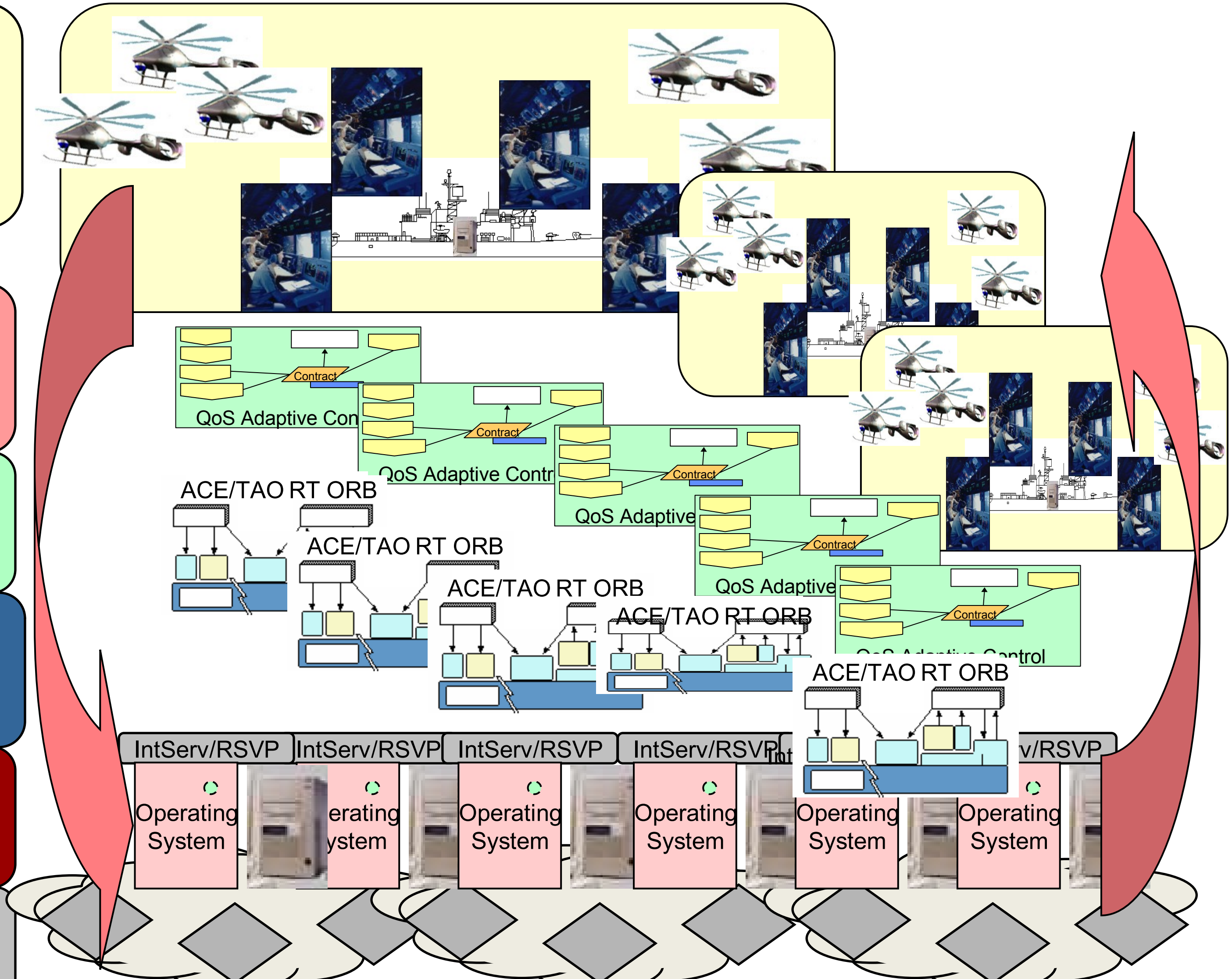
Application or Domain-specific QoS

Common Middleware Services QoS

Distribution Middleware QoS

Operating System QoS

Network QoS



Dynamic Quality of Service is a Key Aspect of Mission Critical Distributed Systems

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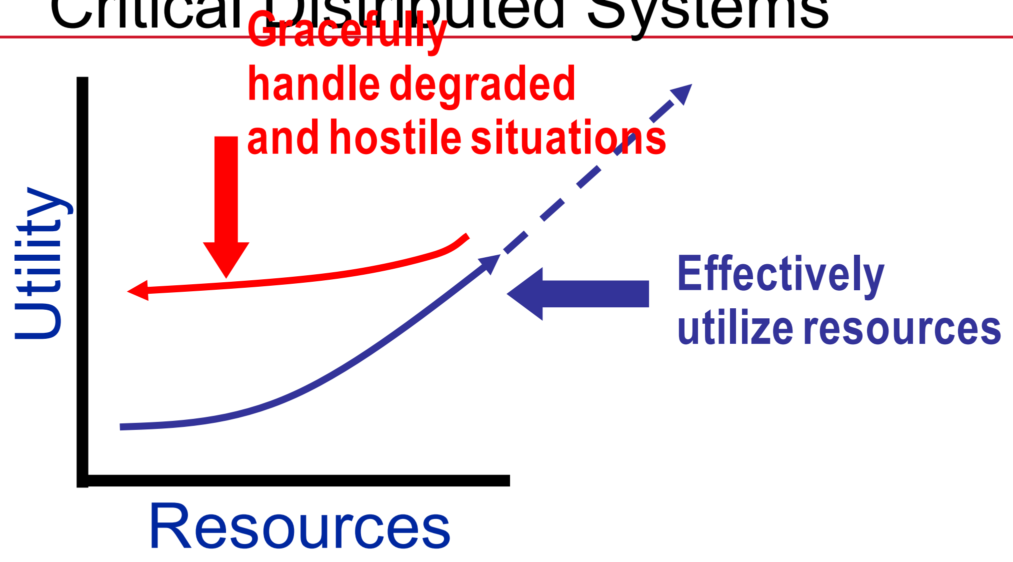


QoS management for distributed systems strives to provide a predictable high level of mission effectiveness and user satisfaction within available resources.

- Capture QoS aspects of mission requirements
- Effectively utilize available resources for mission effectiveness
- Manage the resources that could become bottlenecks
- Mediate conflicting demands for resources
- Dynamically reallocate as conditions change

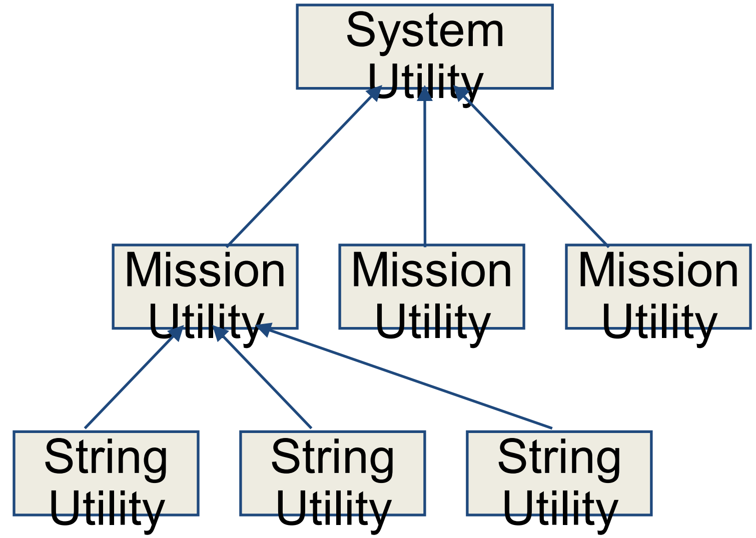
Allocating Resources According to Utility

- How to determine mission utility?
- Each mission has multiple sets of tasks called application strings.
  - Take weighted sum of string utilities

$$UA_i^m = \sum_{i=1}^{N_i} w_j^s UA_j^s$$

  - Weighting for relative importance of strings.
- String utility
- Quality of Service Factors:
  - Timeliness
  - Availability
  - Quality
  - Throughput

$$UA_j^s = F(T, a, q, Th)$$



- *Maximize end-user value!*
- Dynamically adjust resource allocation.
  - -Continuous end-to-end improvement.
  - -Robust to variations in system behavior.
  - -Maximize utility across deployed missions.
  - -Gracefully handle resource failures.

Multi-Layered End-to-End QoS Management

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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

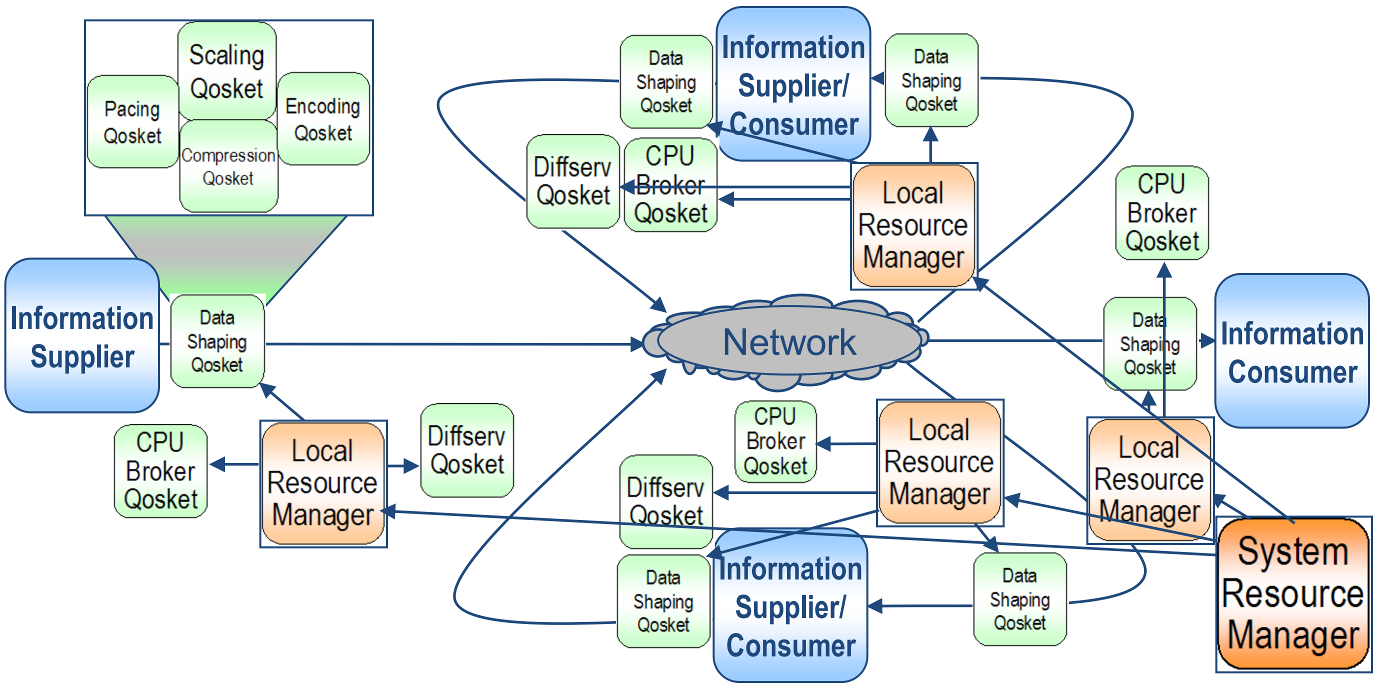
- Set DiffServ CodePoints (per ORB, component server, thread, stream, or message)
- Work with DSCP directly or with higher level bandwidth brokers
- Priority-based (Diffserv) or reservation-based (RSVP)

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

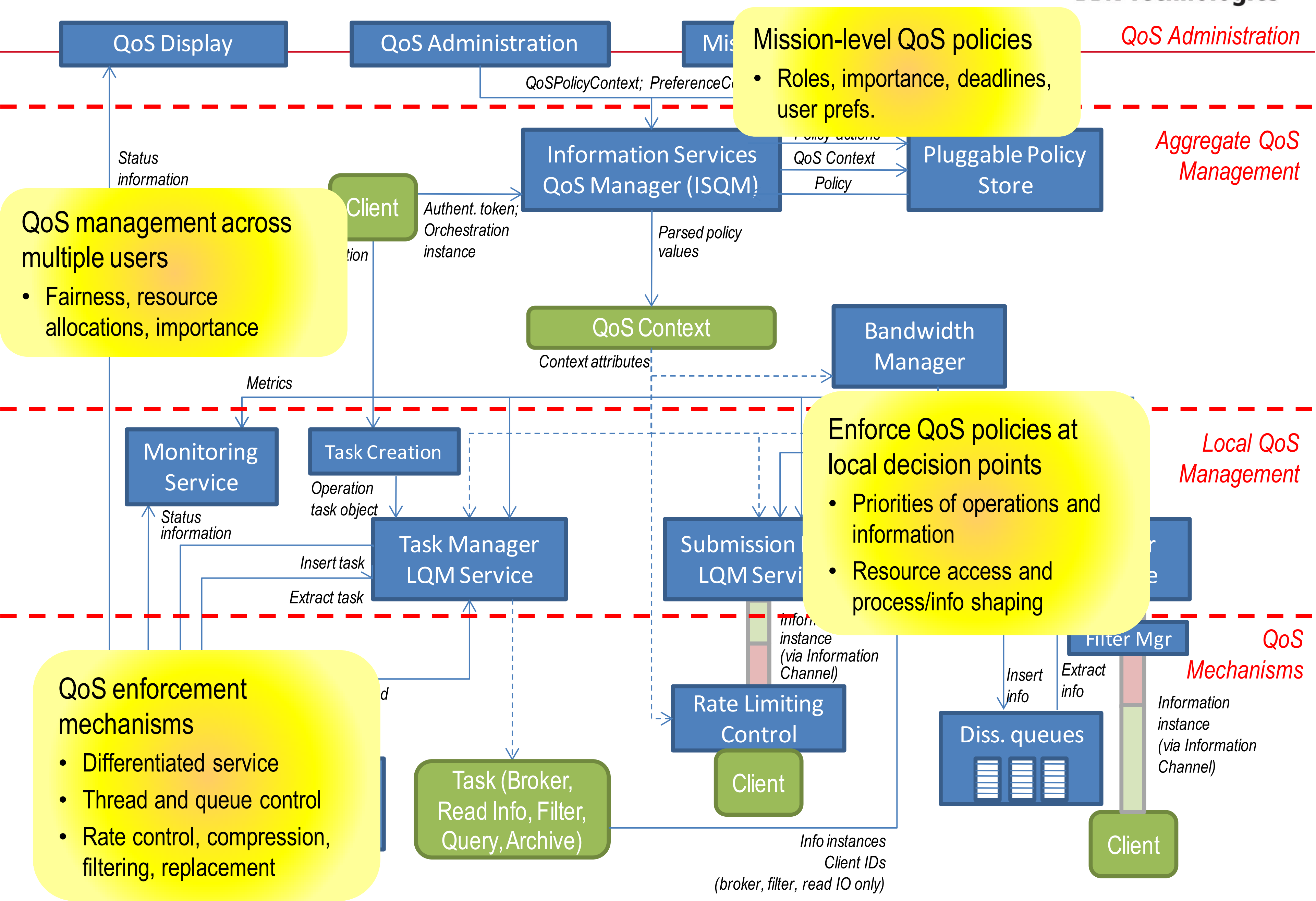
System resource managers allocate available resources based on mission requirements, participants, roles, and priorities

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

2000s Multi-Layered QoS Management for Service-Oriented Distributed Information Systems



From Protection to Auto-Adaptive to Survivable and Self-Regenerative Systems

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No system is perfectly secure– only adequately secured with respect to the perceived threat.

Prevent Intrusions
(Access Controls, Cryptography, Trusted Computing Base)

Trusted Computing Base

Access Control & Physical Security

Cryptography

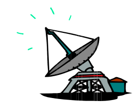
But intrusions will occur

1st Generation: Protection

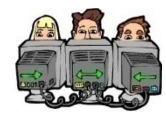
Detect Intrusions, Limit Damage
(Firewalls, Intrusion Detection Systems, Virtual Private Networks, PKI)

Firewalls

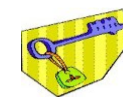
Boundary Controllers



Intrusion Detection Systems



VPNs



PKI

But some attacks will succeed

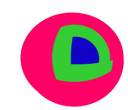
2nd Generation: Detection

Tolerate Attacks
(Redundancy, Diversity, Deception, Wrappers, Proof-Carrying Code, Proactive Secret Sharing)

Intrusion Tolerance

Big Board View of Attacks
Real-Time Situation Awareness & Response

Graceful Degradation



Hardened Operating System

3rd Generation: Intrusion Tolerance and Survivability

Survivability and Intrusion Tolerance

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Premise

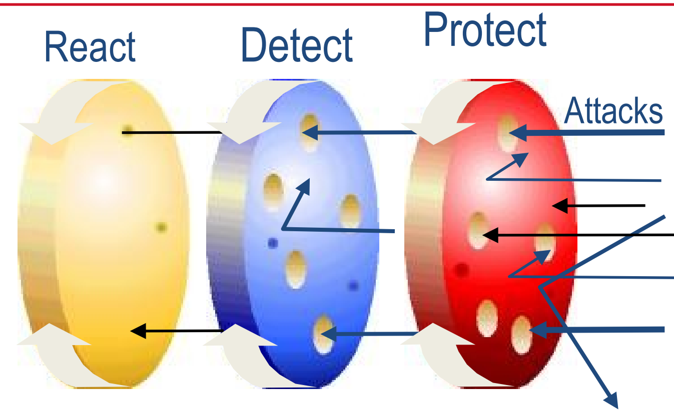
- The number & sophistication of cyber attacks is increasing – some of these attacks will succeed

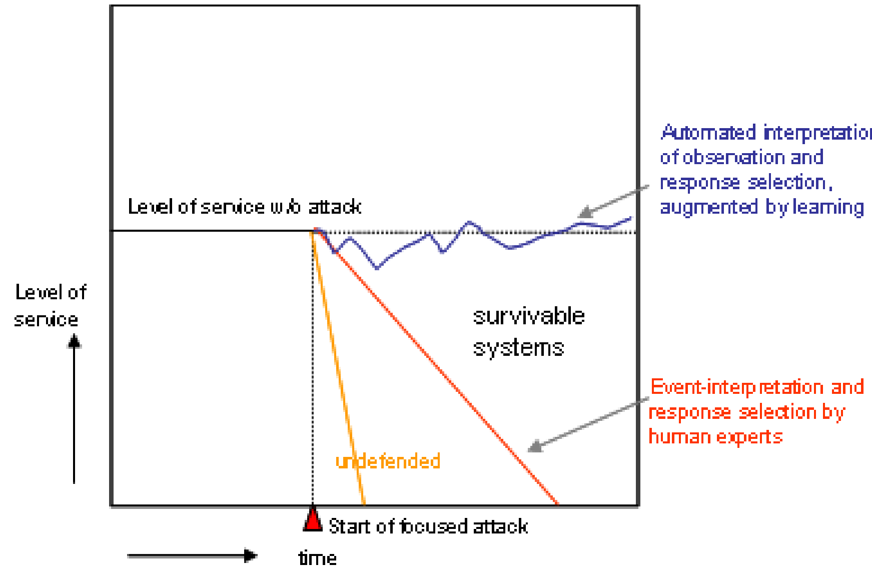
Philosophy

- *Operate through attacks* by using a layered defense-in-depth concept
  - Accept some degradation
  - Protect (C,I, A) of most valuable assets (information, services, …)
  - Move faster than the intruder

Approach

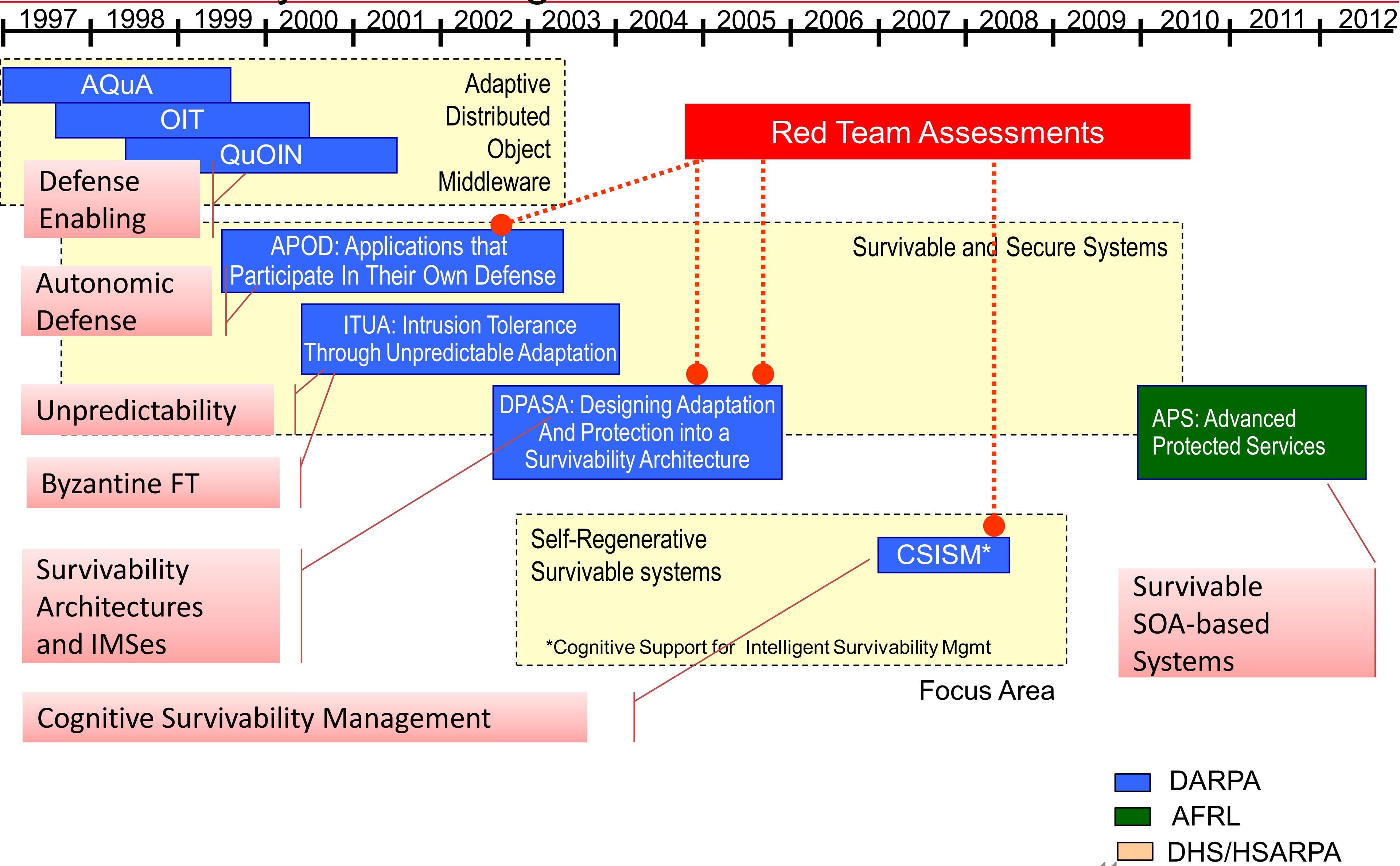
- "Defense Enabling" Distributed Applications
- Survivability architecture





- Exploring beyond degradation-- regain, recoup, regroup and even improve
- Semi-automated: Survivability architecture captures a lot of low level (and sometimes uncertain and incomplete) information – utilizes advanced reasoning and machine learning

Slowly Advancing from Defending to Tolerance to Survivability toward Regeneration



Achievements So Far (2009)

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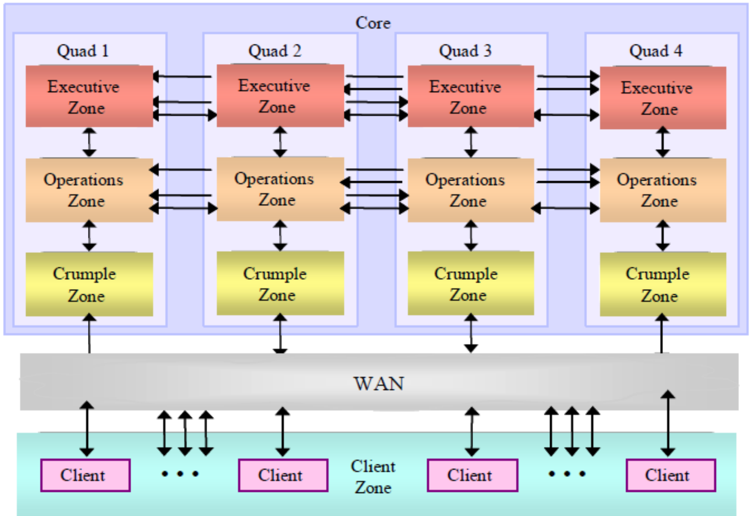
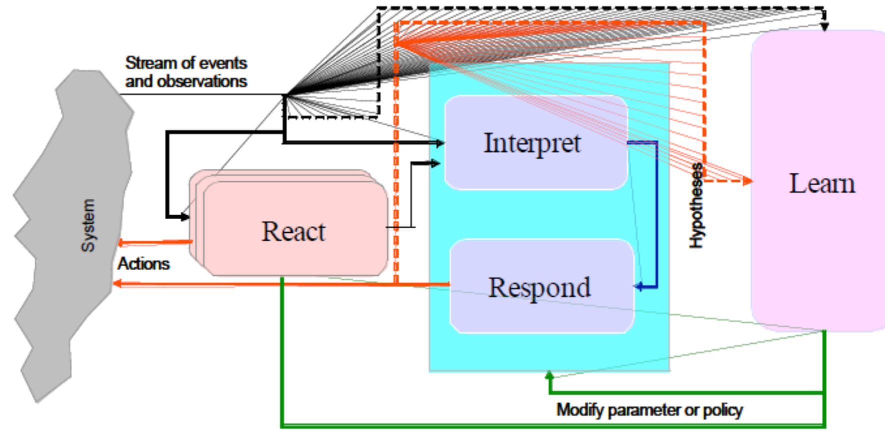


Military (USAF) Joint Battlespace Infosphere (JBI) information management system exemplar made survivable and subjected to sustained attacks over several weeks by multiple independent red teams



Challenge: Develop automated mechanism that would interpret the reports and decide the effective course of action

CSISM Approach: 3 level decision making- reactive, deliberate and learned; use theorem proving and coherence to reason about accusatory and evidentiary information contained in reported events

Results

- The system survived 75% of attacks
- Of those that succeeded,
  - Average time to failure was 45 minutes
  - Vs. immediately in the unprotected system
  - Minimum of 10 minutes to failure
  - Required combinations of attacks
- Adaptive defenses added 5-20% overhead to call latency

Results

- Possible to minimize expert involvement
- Reasoning about accusatory and evidentiary information wrt encoded knowledge
  - Made correct decision in ~75% cases in red team exercises
  - Compute intensive
- Integrating learned responses online needs additional research

Elements of Cyber-Defensive Ideas

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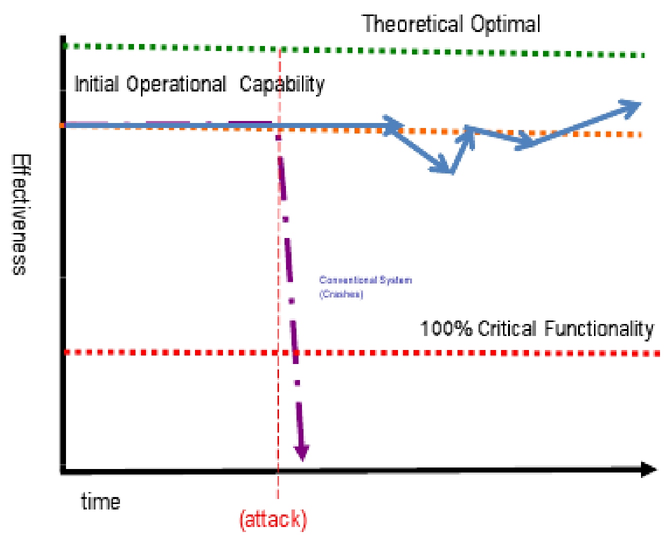
- Common threads that runs through our intrusion tolerance and survivability work:
  - Adaptation for security
    - Like in nature, services migrate; change behavior, structure and configuration in order to survive
  - Unpredictability
    - Changing and taking unexpected actions yield advantages
  - Intelligent behavior
    - Like high order life forms, cognitive capabilities are introduced to survivable systems for interpreting reported events and making decisions
  - Evolution
    - Learning to improve defenses over time

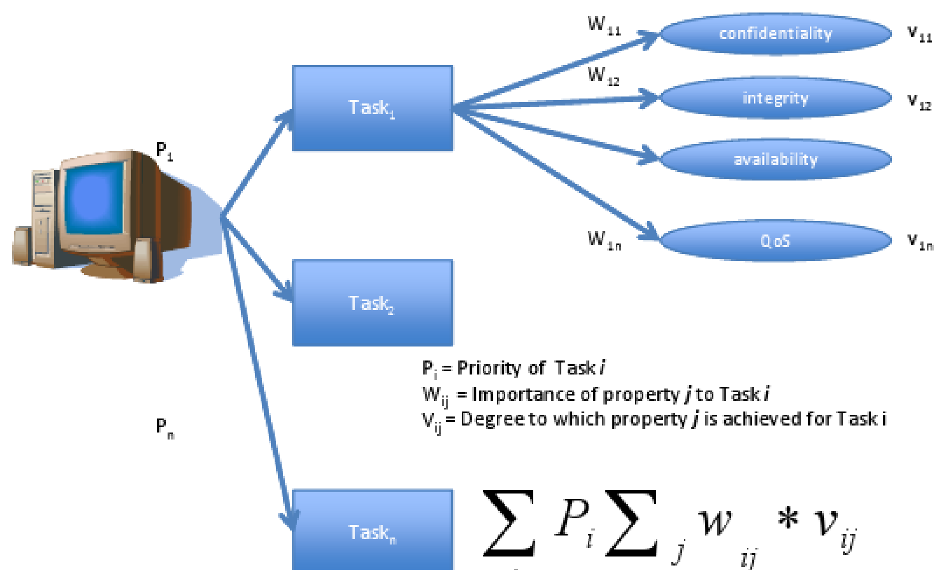
Objectives

The objective is to sustain mission effectiveness. Different mission components have different security needs and will make different trade-offs at run-time between these, quality of service, and even correctness.

- Provide 100% critical functions at all times in spite of attacks.
- Design out the root causes of all current technical vulnerabilities.
- Adapt around corruptions and recover to initial capabilities after penetrations.
- Learn how to defend against new vulnerabilities to improve robustness over time.



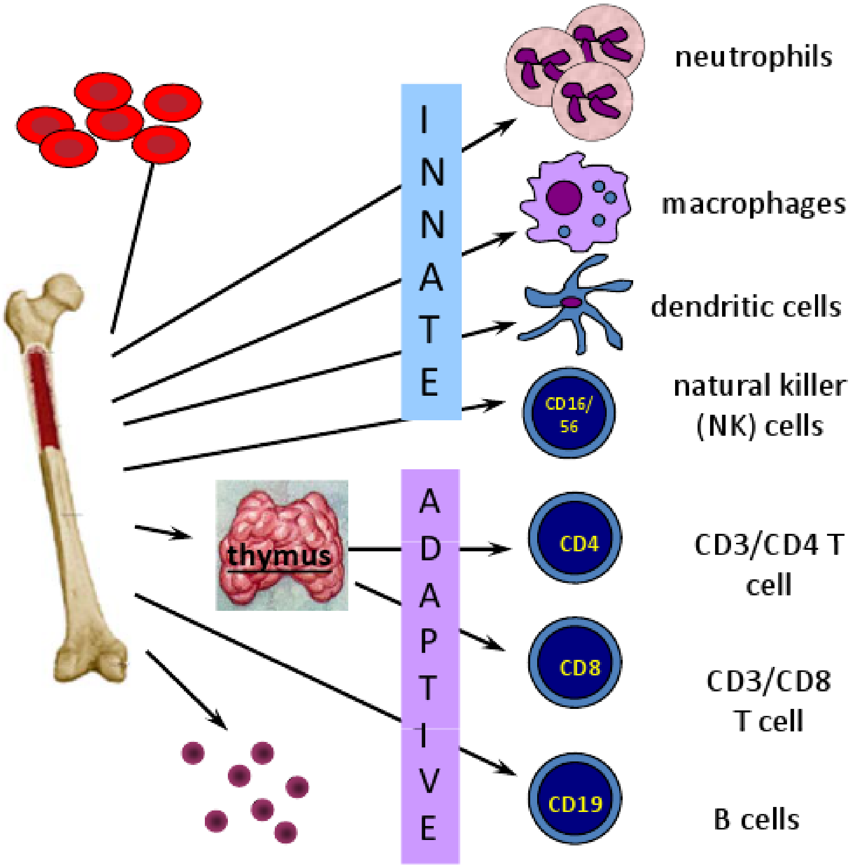
Metric for Mission Effectiveness



$$\sum_i P_i \sum_j w_{ij} * v_{ij}$$

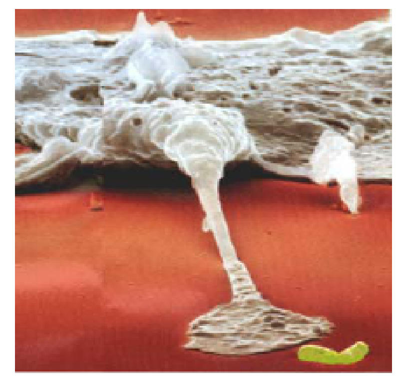
Slide courtesy Dr. Howard Shrobe, DARPA

Humans have Two Immune Systems: Innate and Adaptive



Fast, but inflexible, covers fixed sets of pathogen that are always present. Supports the adaptive immune system.

Slower, learns to recognize new sets of pathogens, distinguishes self from non-self, retains memory to guard against future attacks.



At least 20 – 30% of the body's resources are involved in constant surveillance and containment.

Slide courtesy Dr. Howard Shrobe, DARPA

Advanced Adaptive Applications (A3) Key Objectives

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Demonstrate application centric adaptation for survival – make the “application” survivable and resilient against novel attacks

- An execution environment supporting innately and adaptively resilient applications
  - The protected application is harder to attack, harder to make unavailable, and harder to repeat past successful attacks
  - Isolation from other computation, dedicated to the survival of the protected application
  - Reusable, cost-effective defense near the application and part of defense in depth strategy

The A3 Vision: Integration of 3 Concepts

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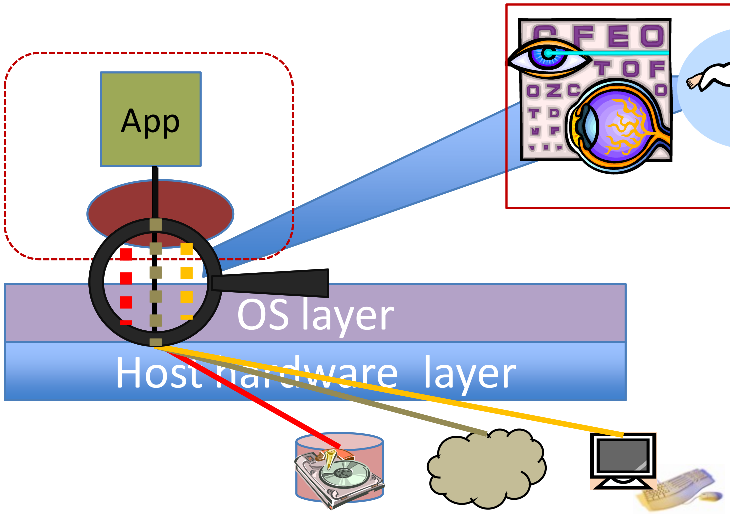
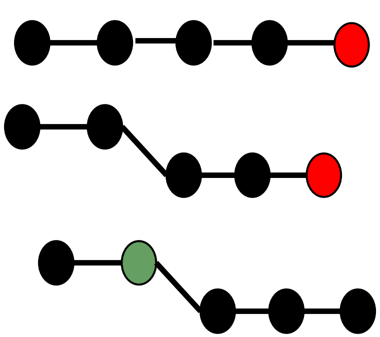


Containerization to isolate application execution

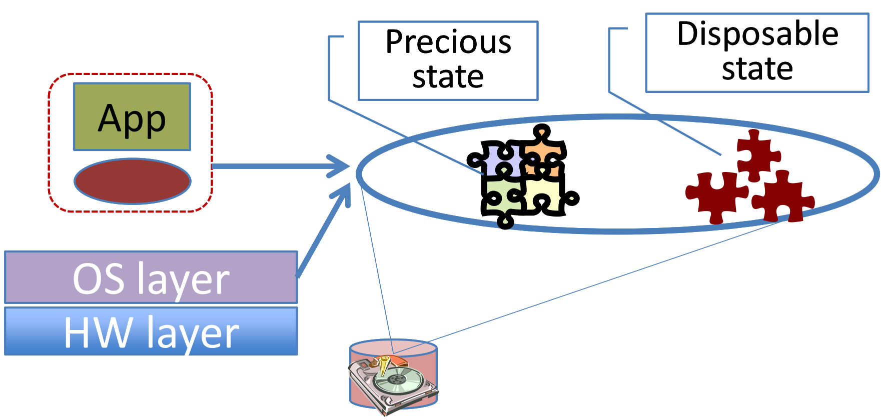
Mediated channels enables the defense to observe and control the application's interaction with devices on its own terms

1. Crumple Zone enforces application specific **preventive adaptation** on container's interaction through mediated channels

2. Replay with Modification on top of mediated containers to facilitate **immunity-focused adaptation**



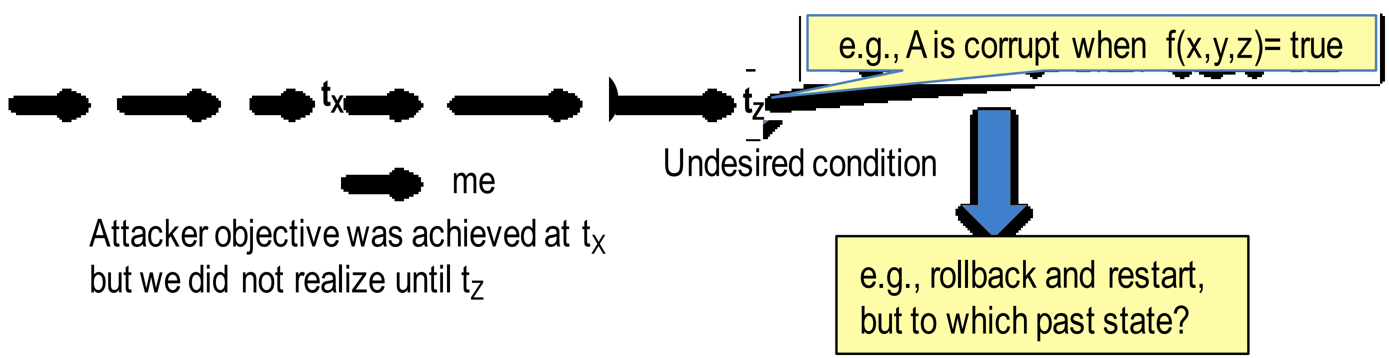
3. Advanced State Management for containerized applications to enable various forms of restarts (**recovery-focused adaptation**)



What is a hard problem: Novel Attacks

- Behavior invariants (e.g., deployer provided constraint such as this web service should never make an outbound connection) or something more drastic (e.g., a segfault) indicates something went wrong
  - But the real attack likely happened in the past
  - Attacker has been successfully executing his tasks
  - And until now, we had no clue

Observed by the CZ policies



- How deal with the aftermath of such attacks?

Work toward immunity
RwM Experimentation

Crumple Zone: VM-based Realization

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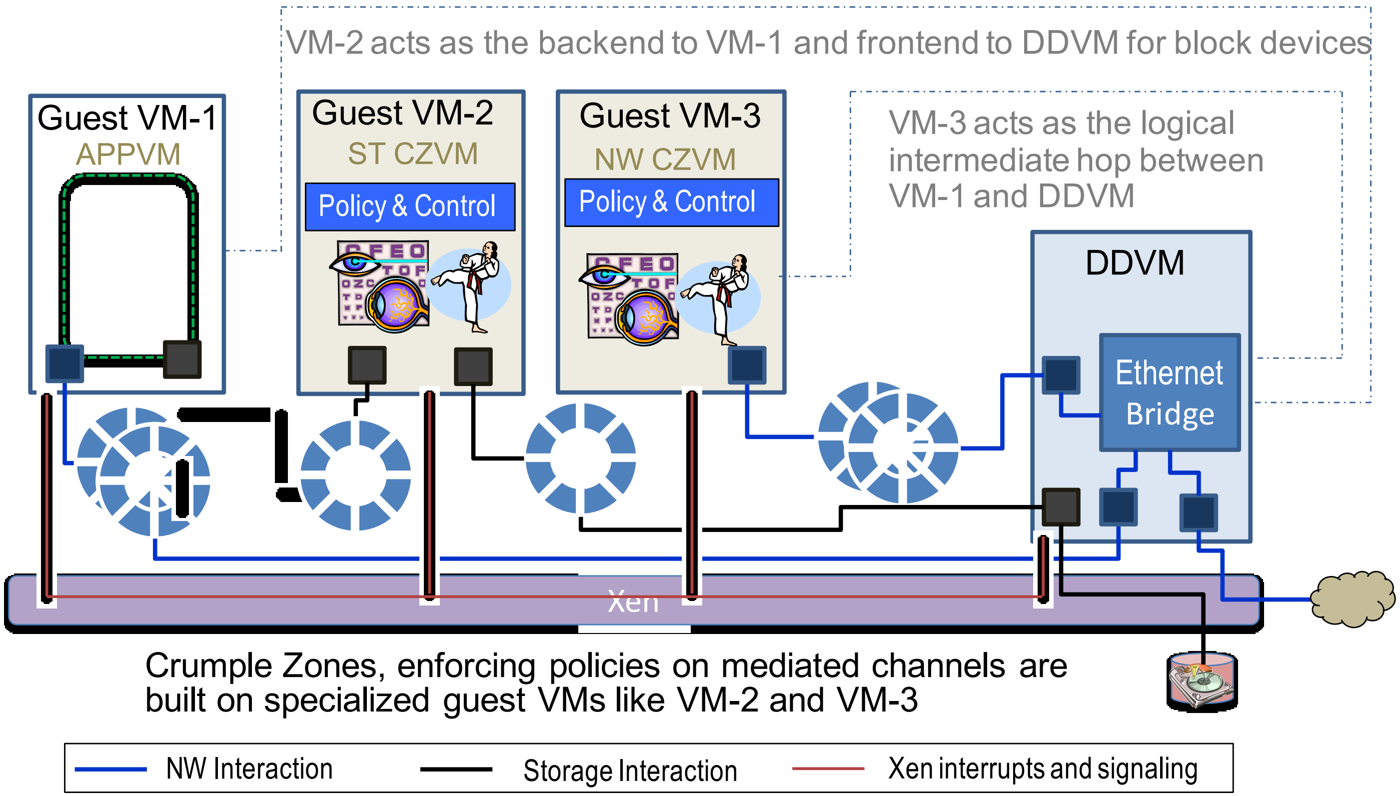
- Each container is essentially a DomU VM
- Channels are pathways from the application to devices (Disk, UI, Network)



Crumple Zone(CZ) are VMs interposed on basic channels

Only the Xen hypervisor and Dom0 is treated as TCB

A3 Conglomerate: the collection of VMs dedicated to the defense of a protected application

Replay With Modification: Motivation

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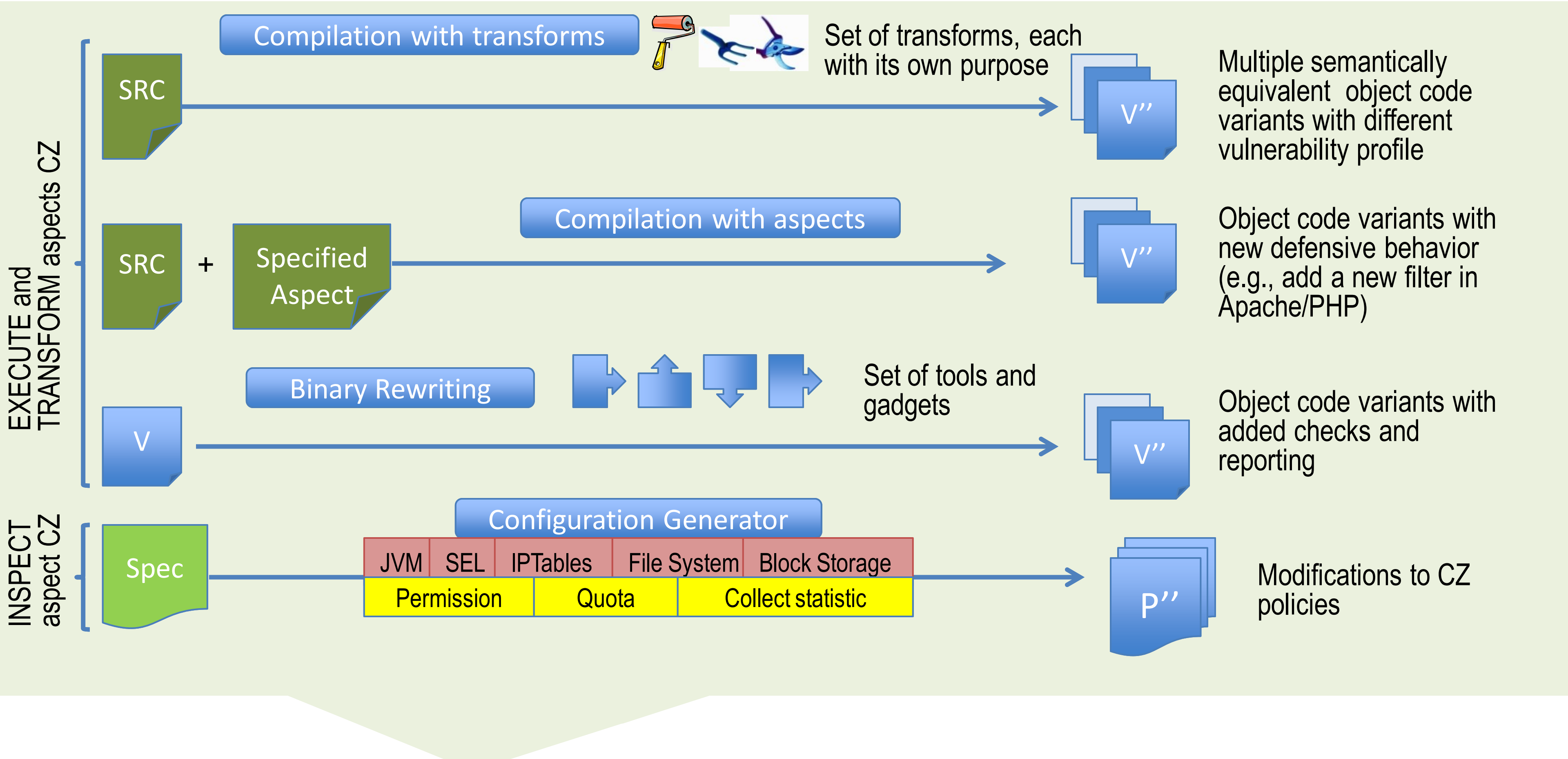
- In a clean slate resilient and survivable host system context, it should be possible to
  - Reproduce application's past execution
    - With *different levels of fidelity and control* in a *repeatable* manner
  - Explore alternate execution history
    - Alternate line leading to an immune conglomerate
    - Exploration of multiple lines unveiling details of novel attack faster
- RwM is A3's contribution to address novel attacks
  - If an immune conglomerate is found, then that attack is ineffective
  - Provides an infrastructure as well as the collection of recorded information and supporting tools for analysts and cyber defenders to analyze a zero day attack and develop a countermeasure
- 2 levels of replay: Deterministic VM replay and Application Level
- Claim: synergistic combination is helpful in experiment-based failure diagnosis and patch identification

Multi-Compiler Variants: Utilizing A Diversity Generator



This is what is happening inside the diversity generator

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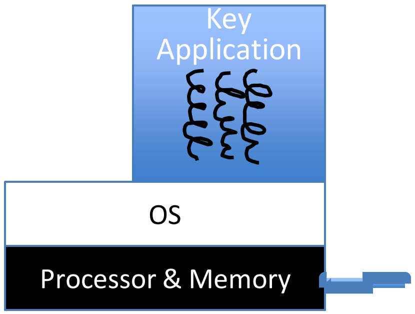
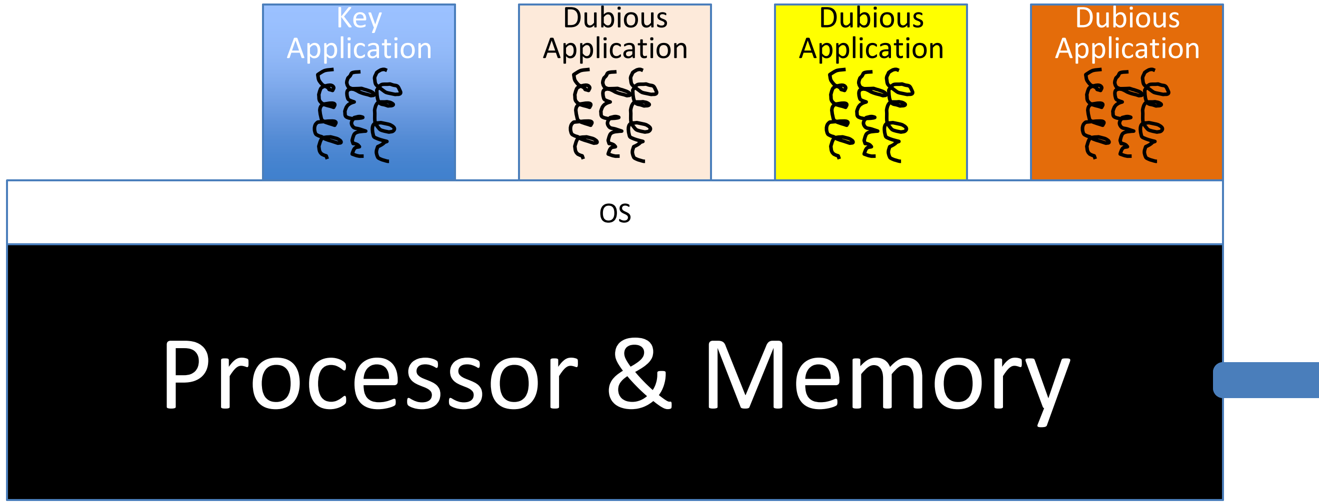
Multiplicity?



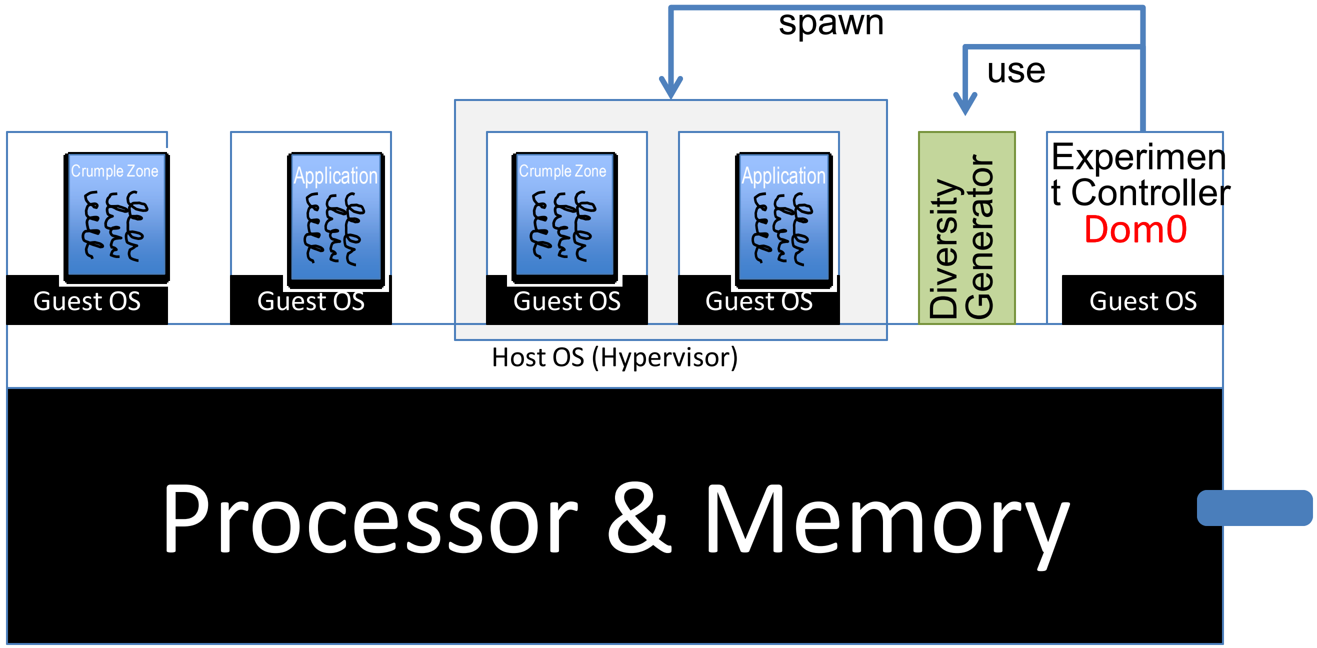


Traditional
- Cpu
- OS
- Memory
- Network connection

Now/Emerging
- Multiple cores, with powerful cpus
- Powerful “feature rich” OS
- Mega memory
- High bandwidth always on network connectivity

Cyber security becomes an obvious context

Multiplicity?



Record and replay, experiment-based diagnosis, patching and recovery!
Use diversity generator to create polymorphic components that exhibit different vulnerability profile

Suddenly resources may not be that bountiful!

Multiplicity?

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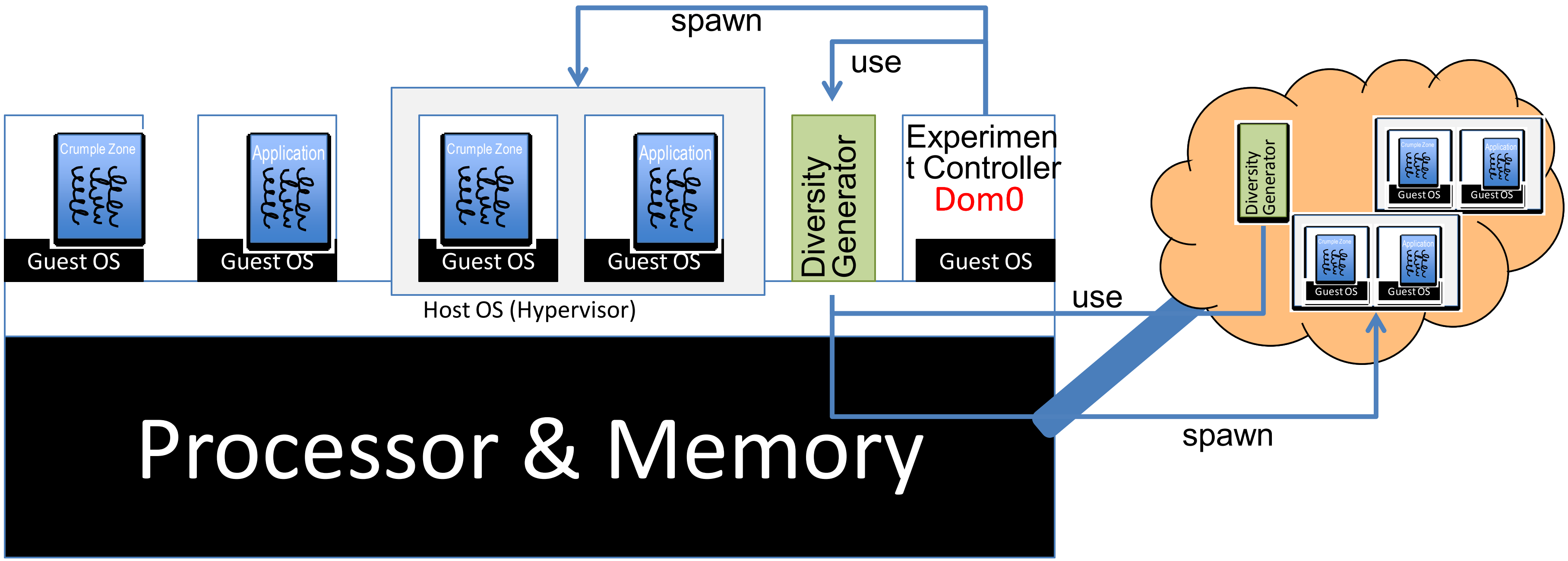

But wait– clouds are gathering steam!

Recorded information, Replay experiments, Diversity generation, Experiment-based diagnosis and patching all can potentially be done in the cloud!

But have we come full circle? Do we really trust the cloud with our critical data and computation?

Fully Homomorphic Computing
Computing Directly on Encrypted Information

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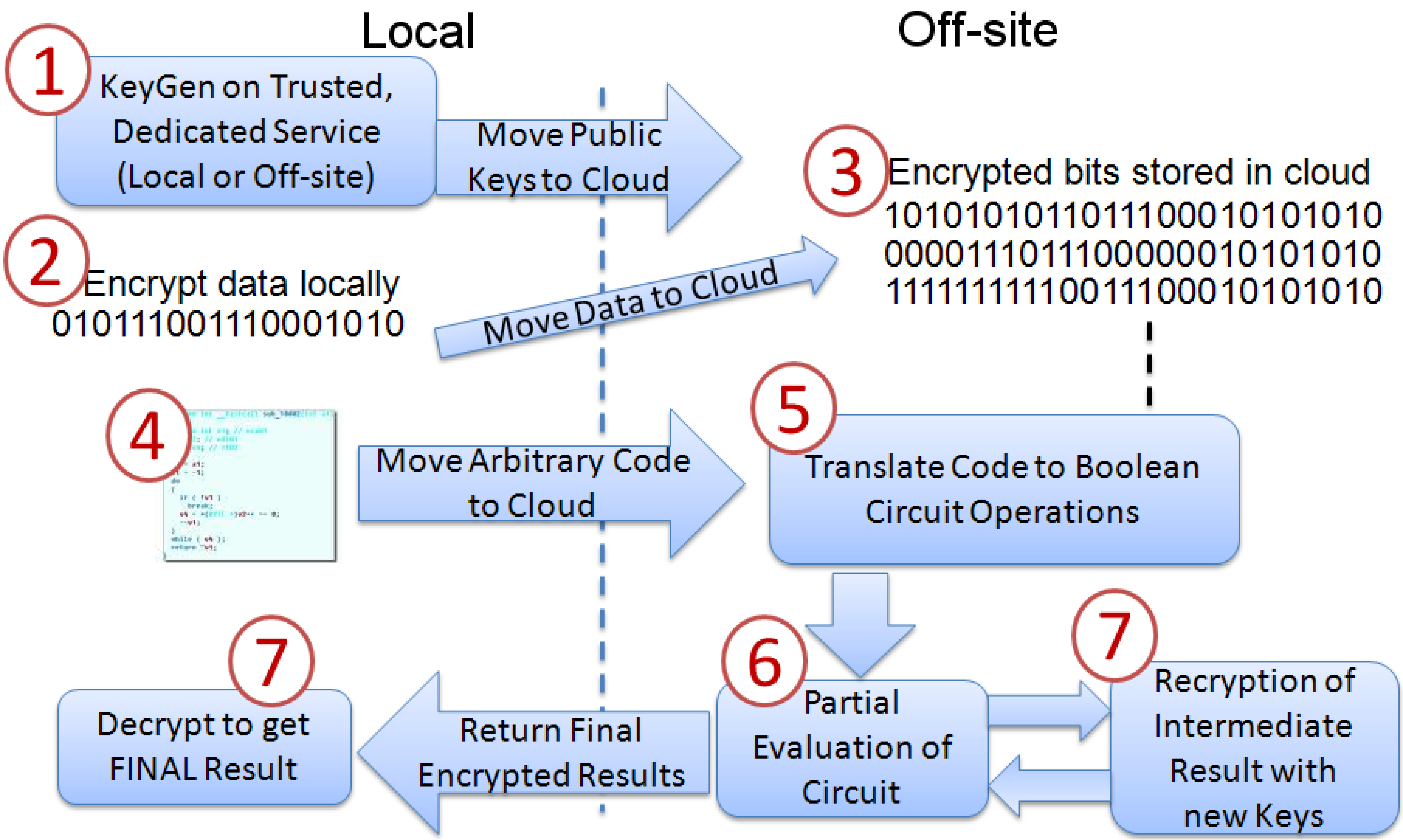

Noise in Ciphertexts

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- Ciphertexts are a combination of noise, the public key and a message.
- The public key is a combination of noise and the secret key.
- EvalMult operations “multiply” the noise in the ciphertext.
- Decryption operations strip away the noise.

Huge Amounts of Data and Computation Beget Special Purpose Solutions

Computation Flow On Untrusted Host

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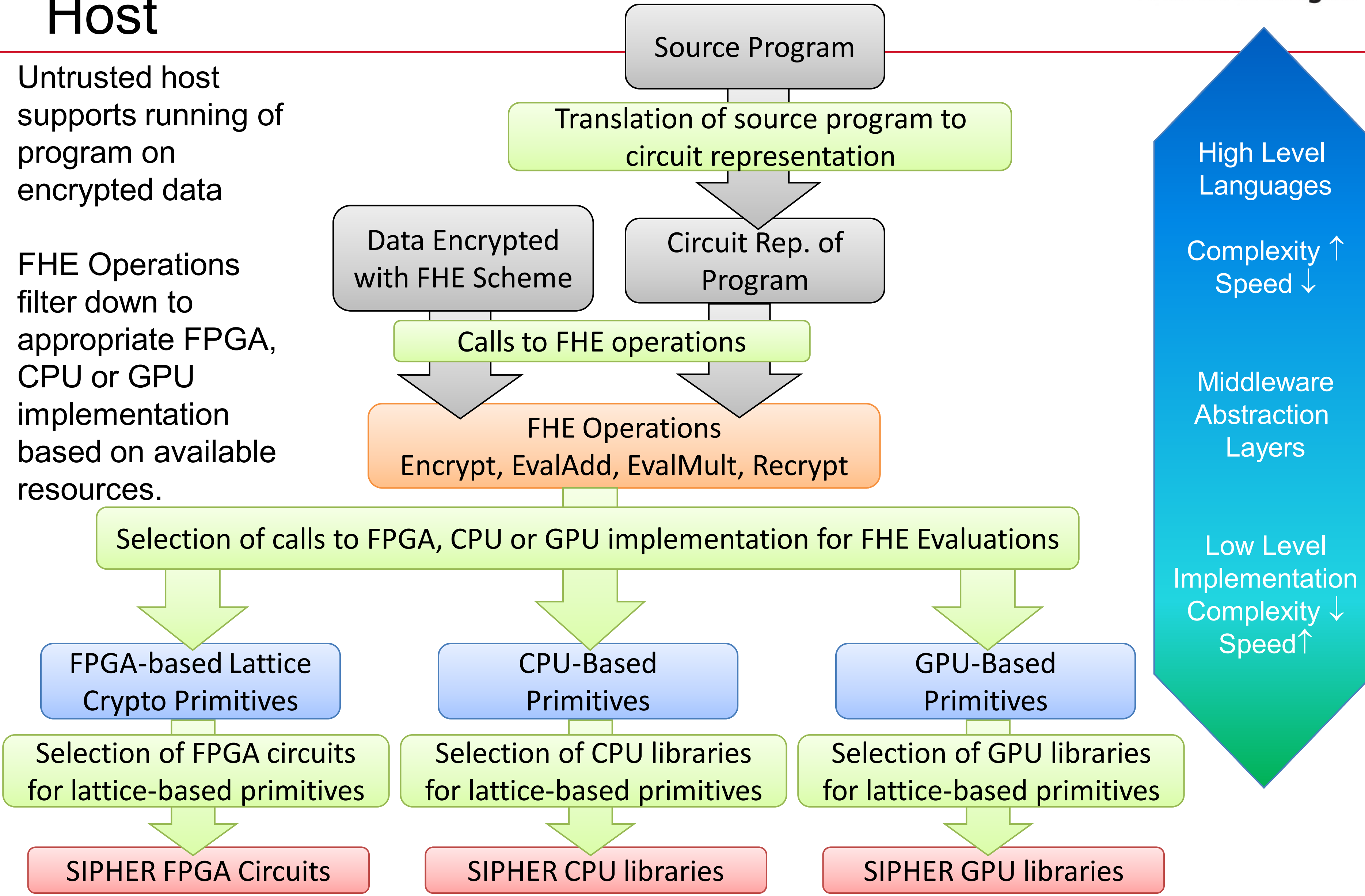
Untrusted host supports running of program on encrypted data

FHE Operations filter down to appropriate FPGA, CPU or GPU implementation based on available resources.



Asymmetric Operation Location Considerations

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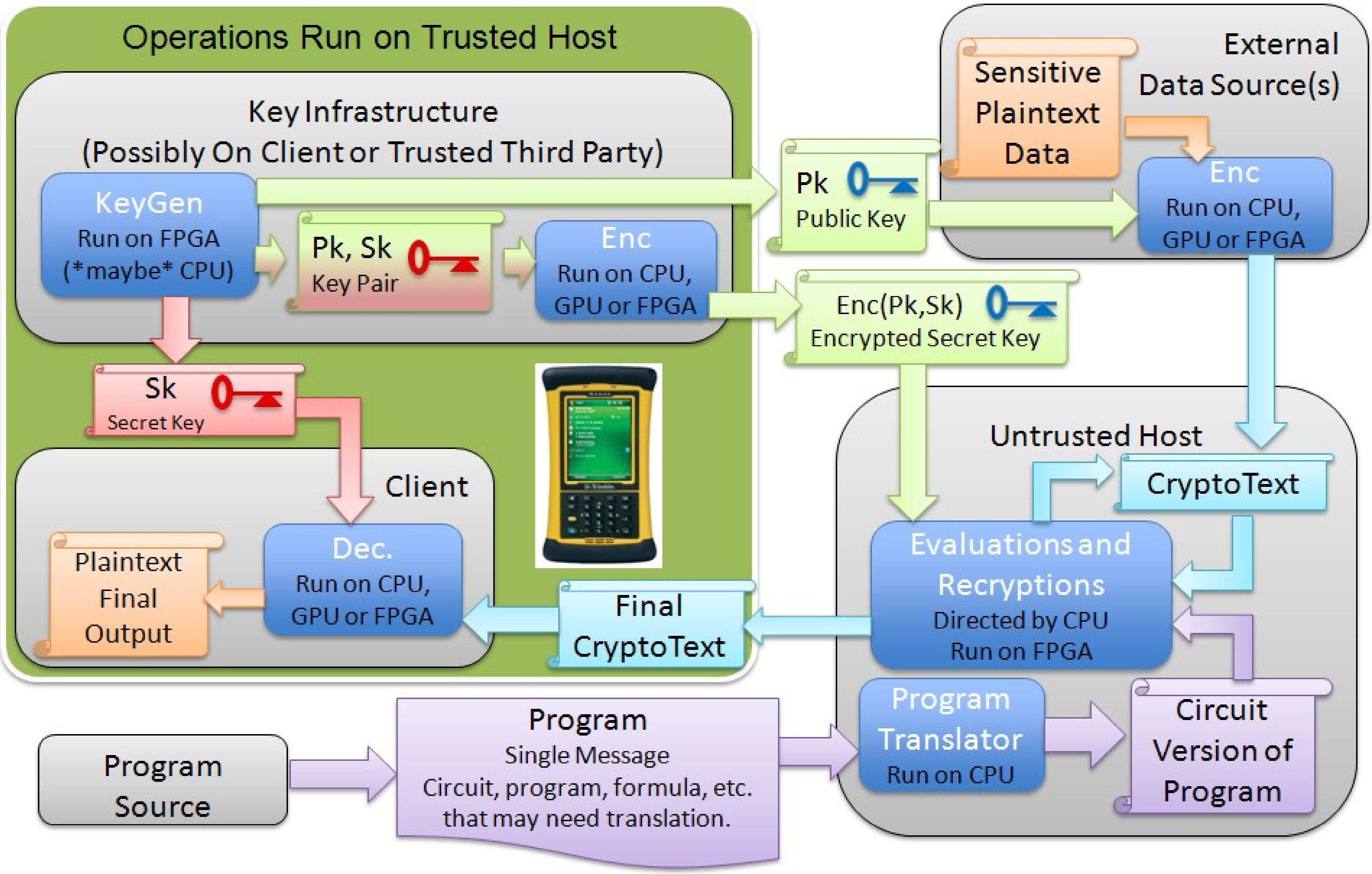

Whew!

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- The Big Bang (of Higher Performance Networked Diversity) Continues to Inflate
- Lot’s of Bottom Up Momentum Building across a number of planes to use that advancing Multiplicity
- Needs coupling with more Top Down concept-of-operation/theory weaving
- And Plenty More to Do to Keep Us Busy for a Long Time