Active Networks: A Tutorial

Spring School, Lenk, CH
March 6-10th, 2000

Jonathan M. Smith
University of Pennsylvania
http://www.cis.upenn.edu/~jms

Tutorial Outline:

- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

Tutorial Outline:

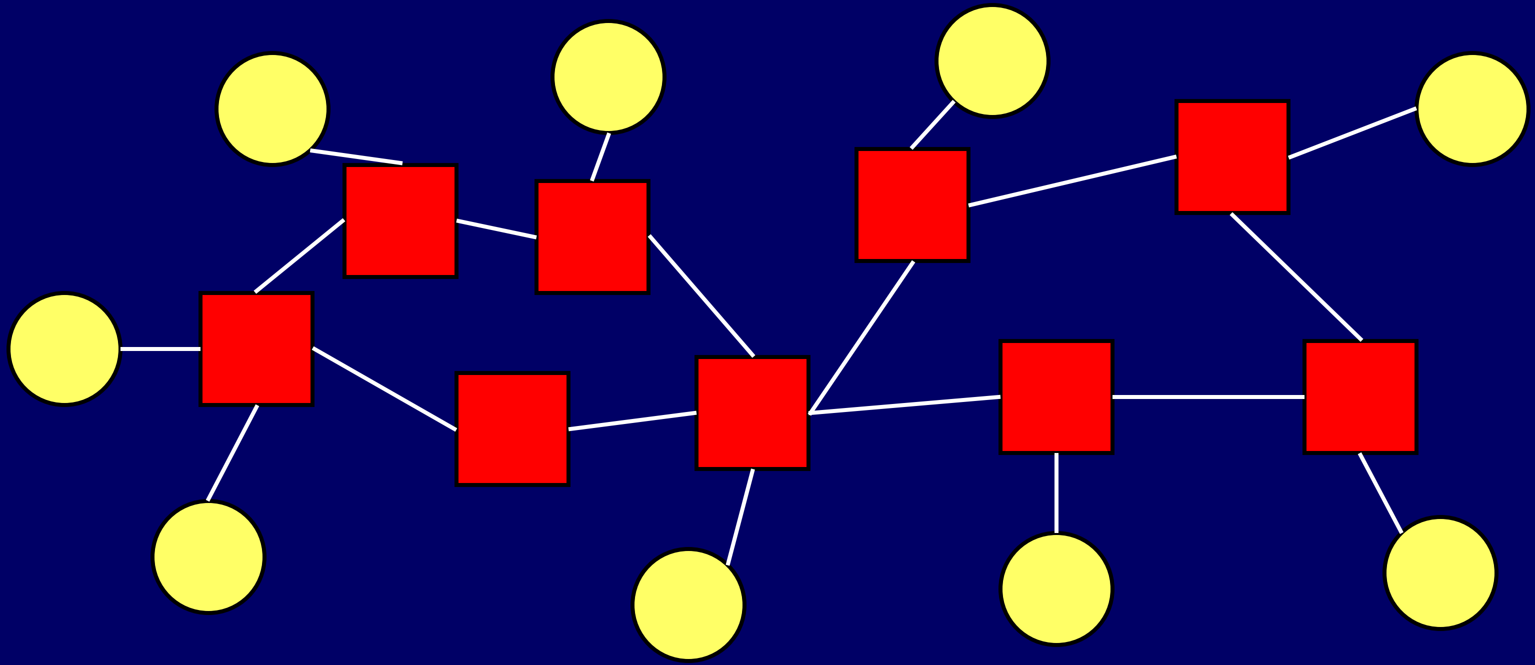
- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

1. Introduction

- Store & Forward versus Store, *Compute* & Forward
- Passive versus *Active* Networking
- An Example Application - Active Reliable Multicast (ARM)
- The Design Space

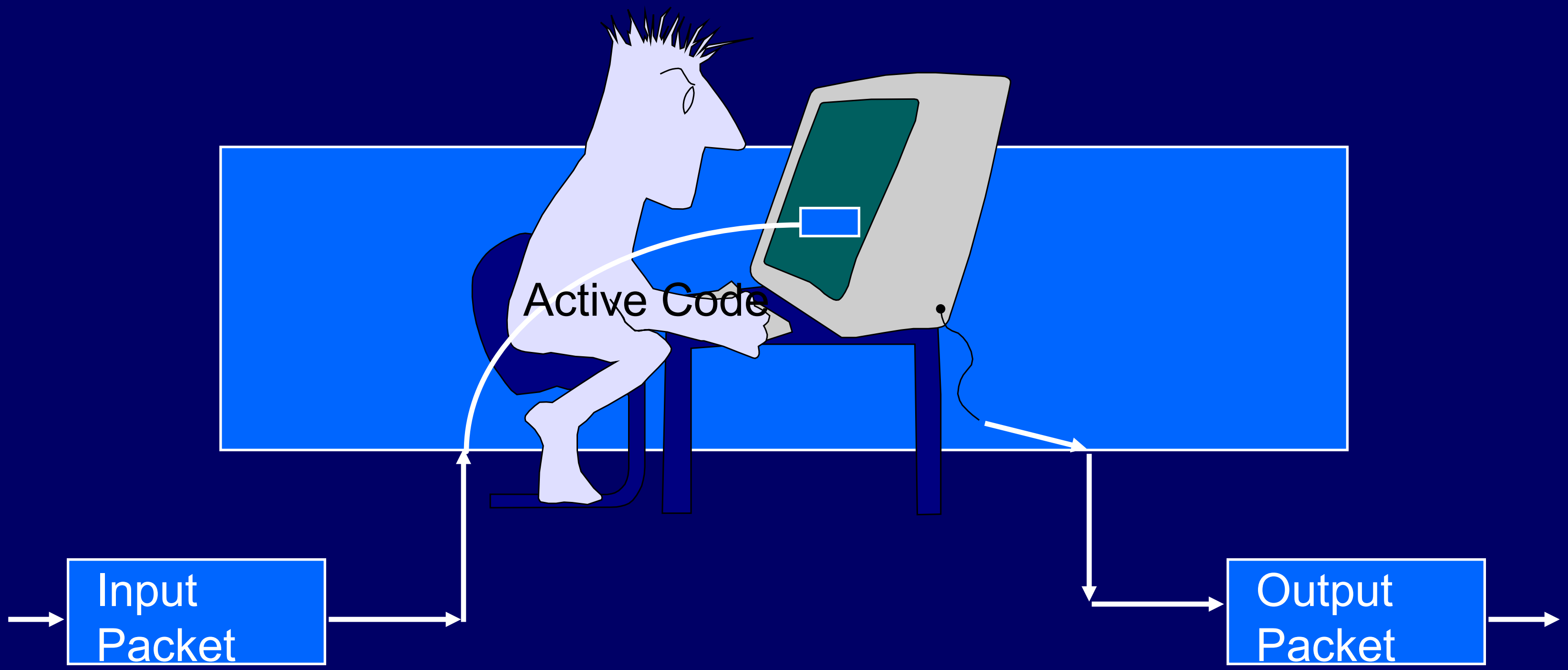
“Passive” Networking

- Smart hosts on the edges
- Passive switches in the center



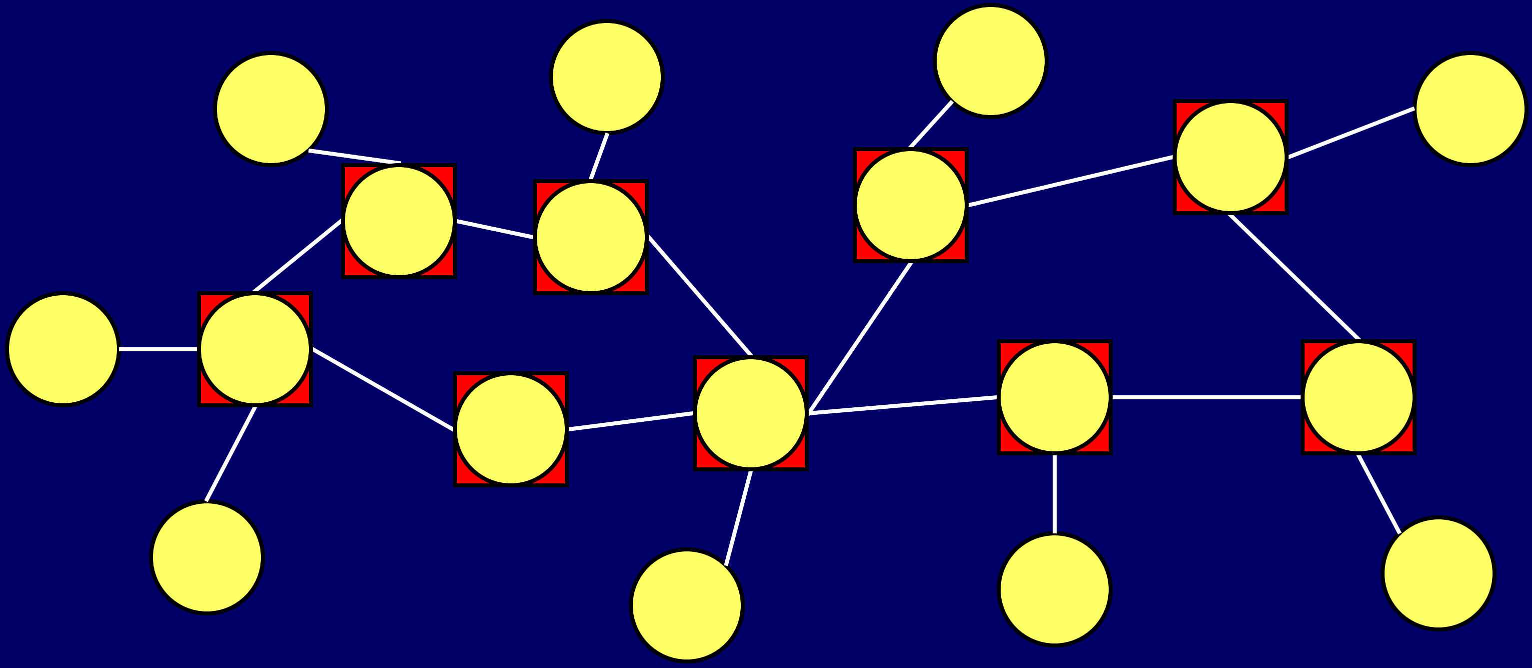
Active Networking Nodes

- Store, COMPUTE and Forward!



Active Network Model

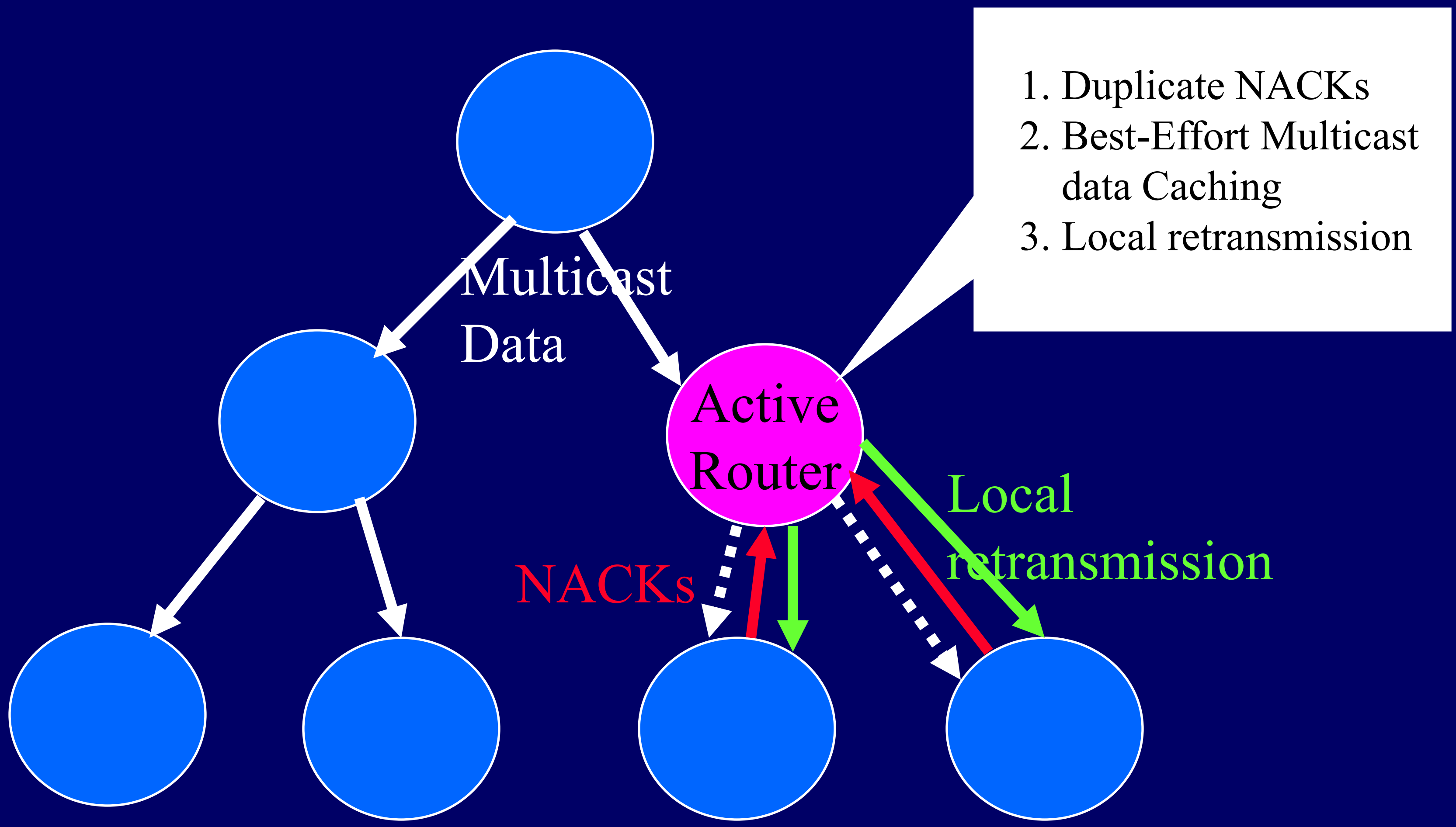
- Packets can change the behavior of the switches "on-the-fly"
  - → In-band active packets
  - → Out-of-band active extensions



An Example Active Application: Active Reliable Multicast (ARM)

- Reliable Multicast plagued by "ACK implosion" when an error occurs
- Retransmission expensive
- In MIT's ARM, Active Elements are embedded in the multicast tree (not all tree nodes need be active for ARM to work)

Example Application: ARM



Outline: the Design Space

- Usability *vs.* Flexibility *vs.* Security *vs.* Performance
- There may be unattractive tradeoffs, e.g., Performance and Security may be inversely related! (also Usability?)
- Usability and Flexibility can (mostly) be obtained with a general-purpose language such as Java, Caml or Forth

Tutorial Outline:

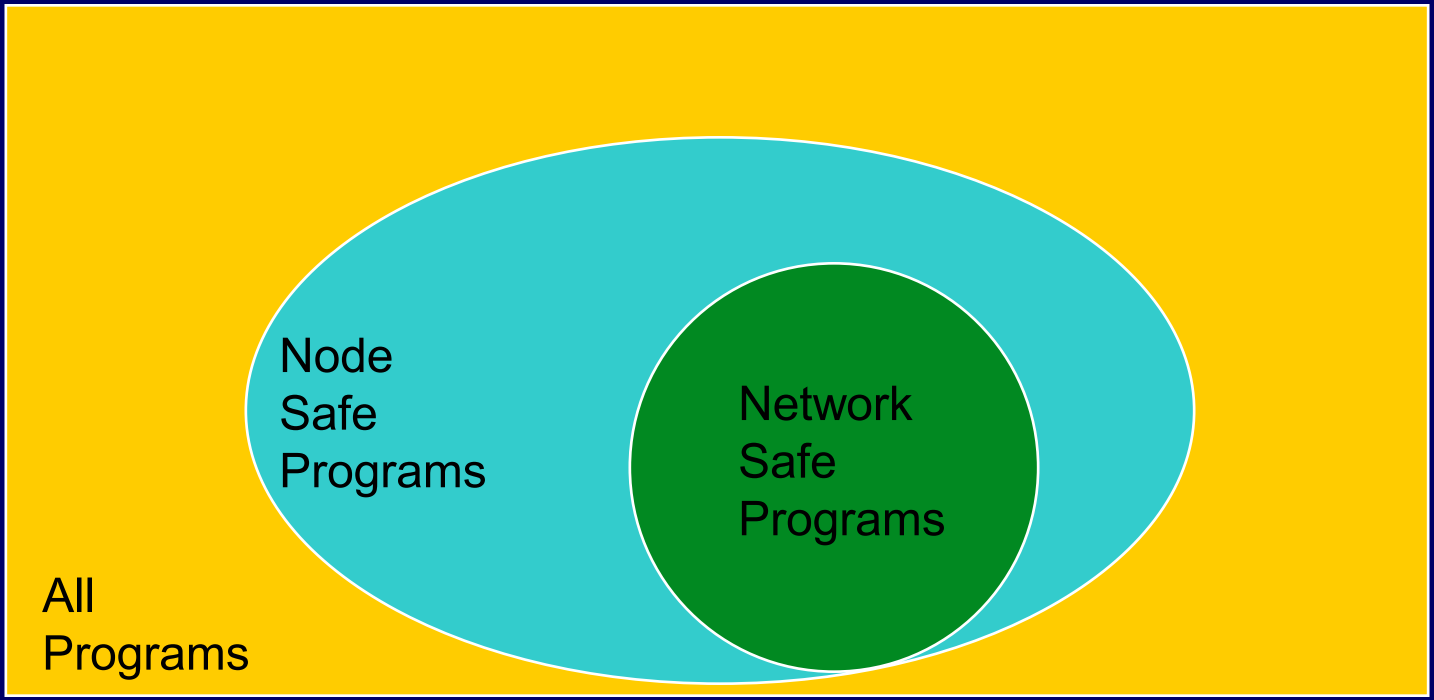
- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

2. Security Challenges

- How can we restrict programs?
- What are safety and security?
- Denial of Service Attacks
- Multiplexing Points
- Local Versus Global Control
- Packet Security

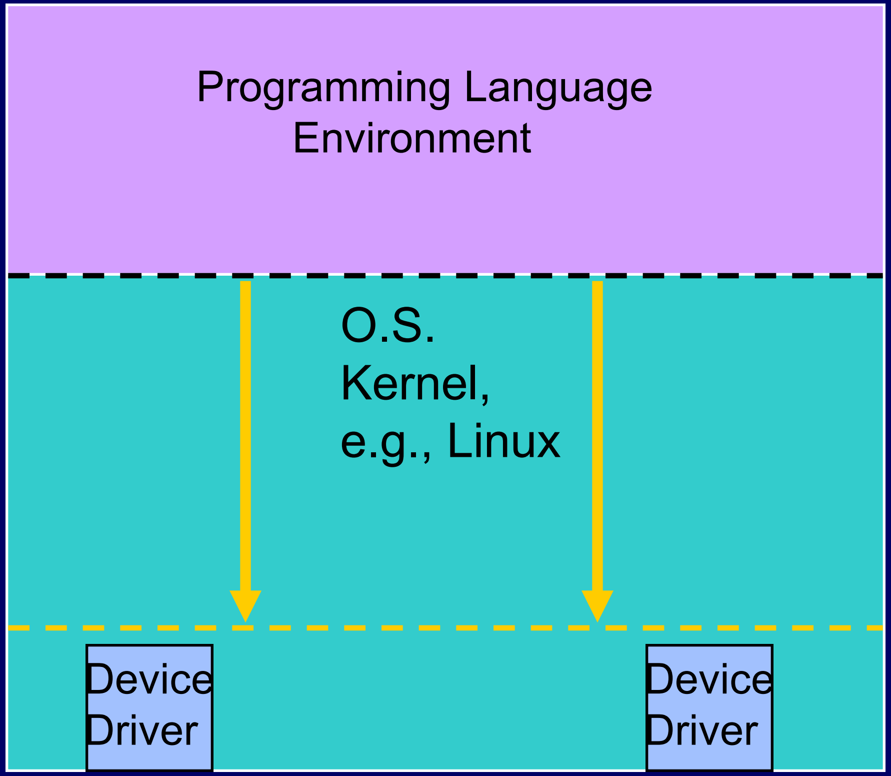
Restricting Programs

- Node safe versus network safe



How do we control programs?

- Safety & Security: P.L., O.S. or hybrid?



Challenges: Safety & Security

- Safety: Accidents; Security: Malice
- Specification of goal (@30,000 feet!):
  - → *Right* Information to
  - → *Right* Place at
  - → *Right* Time
- Insecurity: Deviation from goal
  - → e.g., information to *wrong* place

Right information/Right place

- Requires identifying information units
- Requires identifying places
  - e.g., locations, personnel, etc.
- Requires *security association*
  - e.g., per-place *password* encrypts info.
  - deny information to other places
  - cryptographic protocols: good progress

Right Time (the tricky one)

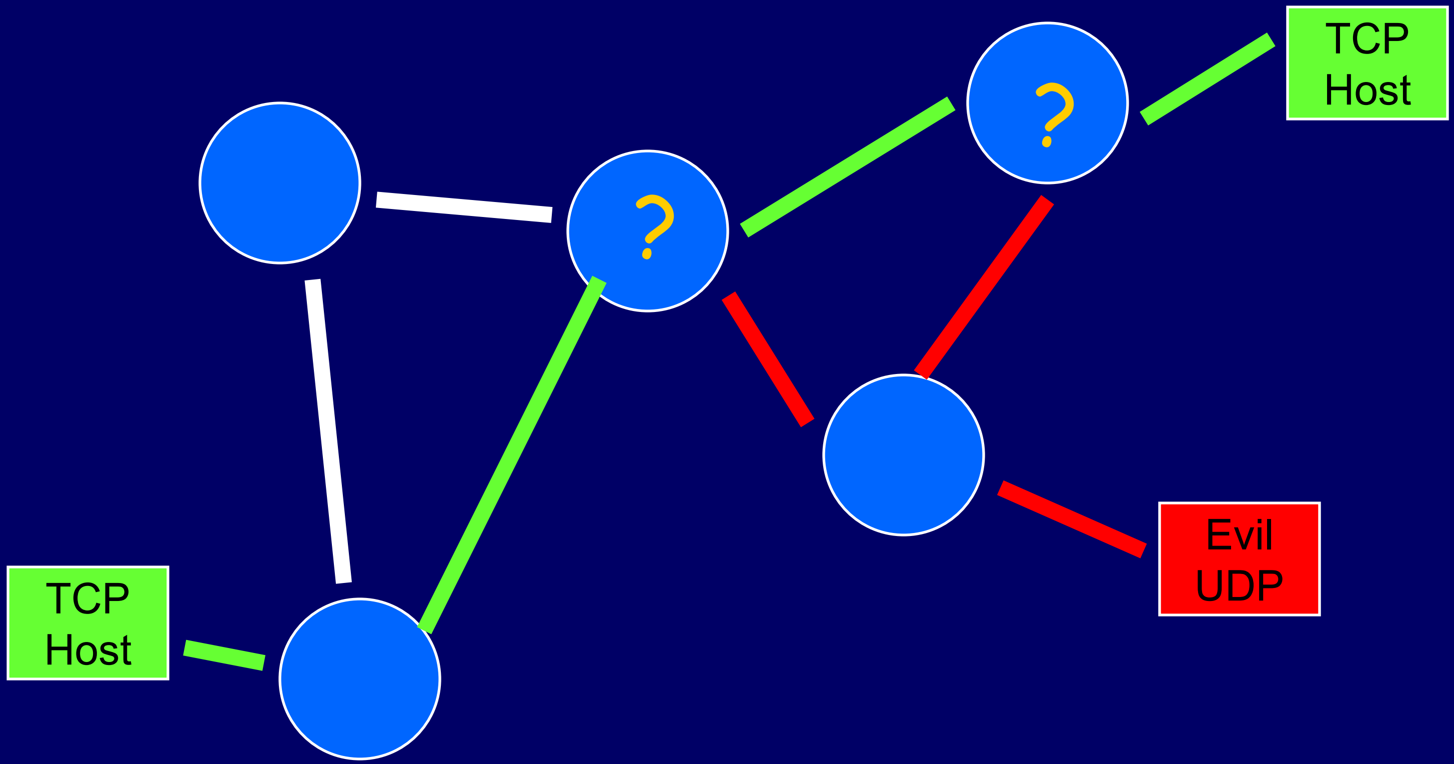
- Late information may be useless
- Basis of *denial of service* attacks
- Requires identifying *real* times
- Languages have no time semantics
  - → gettimeofday() in C/Unix world
  - → is ML better? (Dannenberg's *Arctic?)*

QoS & Security: Denial of Service

- Easy to protect server hosts
  - Resource domains, interrupt masking, firewall shielding on host *itself*
- But service is unprotected between client and server site
- This problem *must* be solved with network-embedded functionality

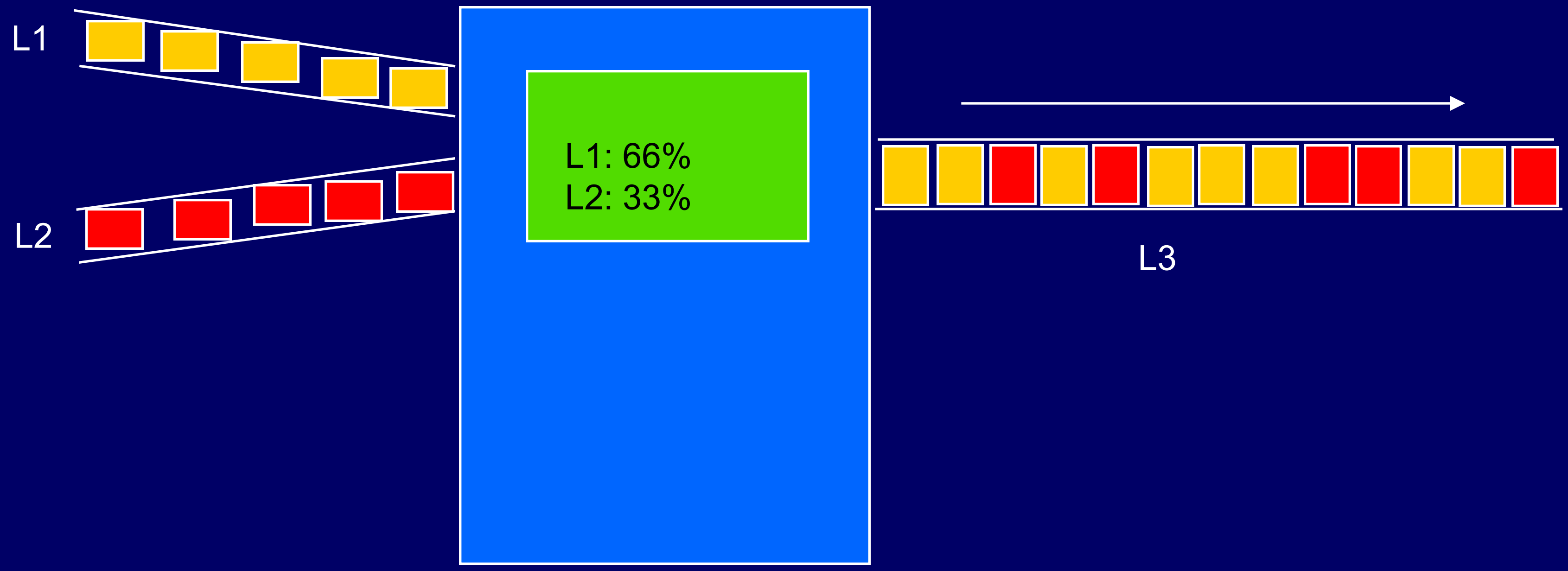
Denial of Service attack

- Cross traffic in an Internet

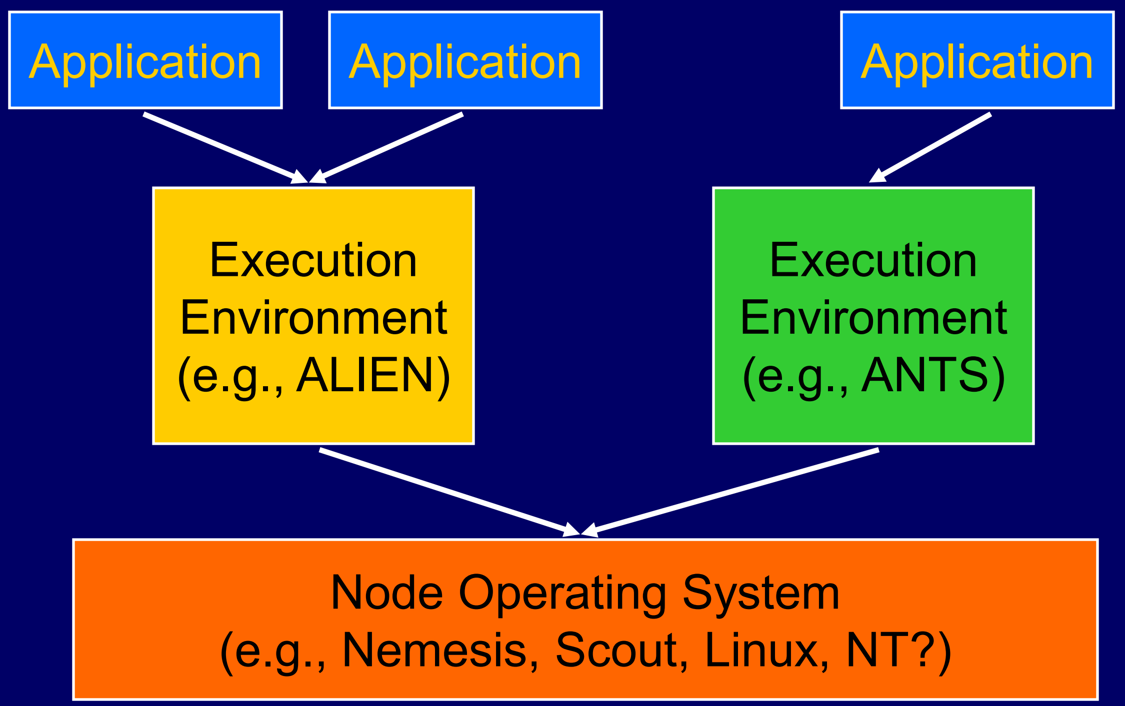


Need to control multiplexing

- E.g., assign L3 bandwidth 66%/33%

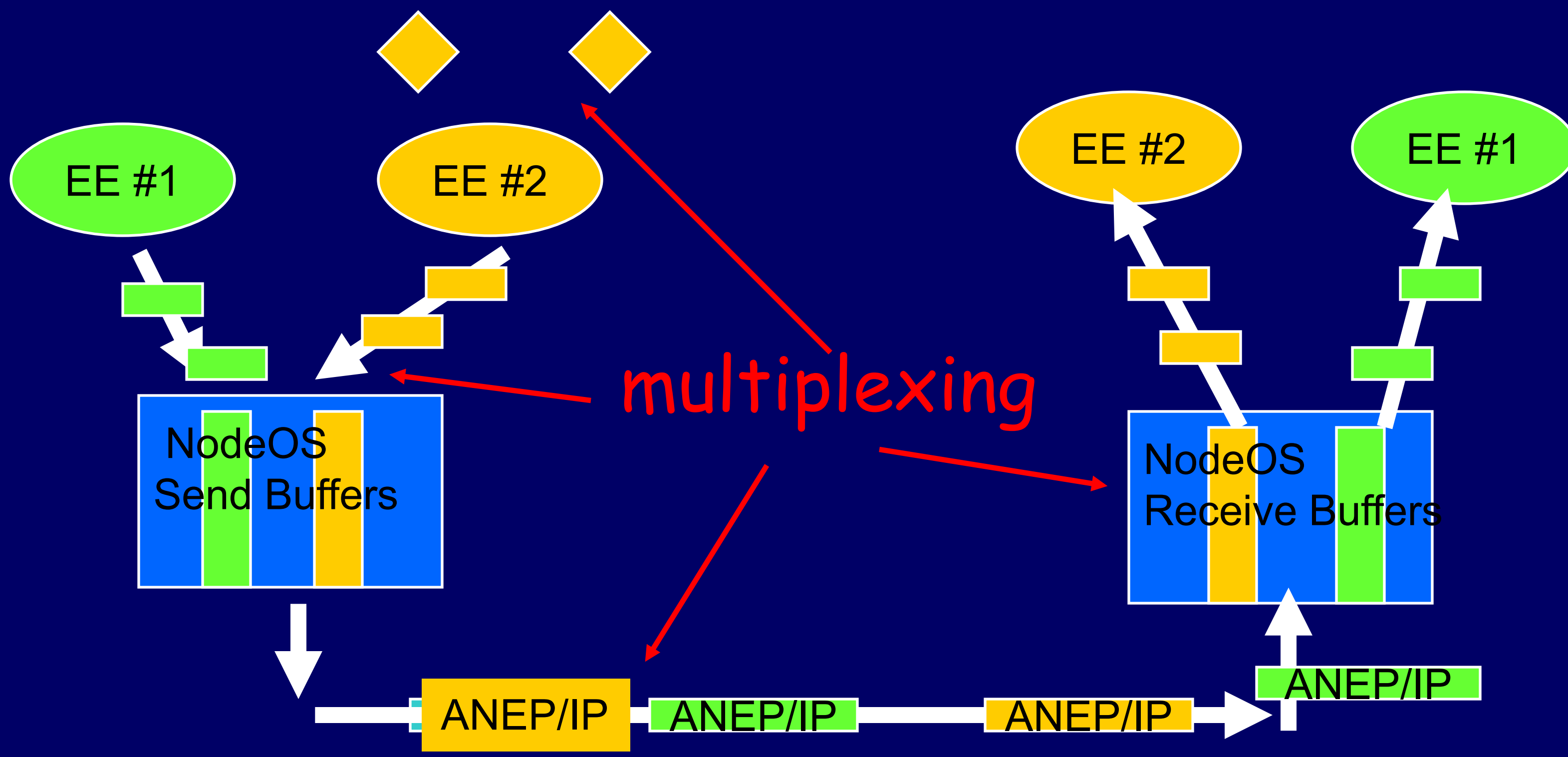


Active Network Architecture



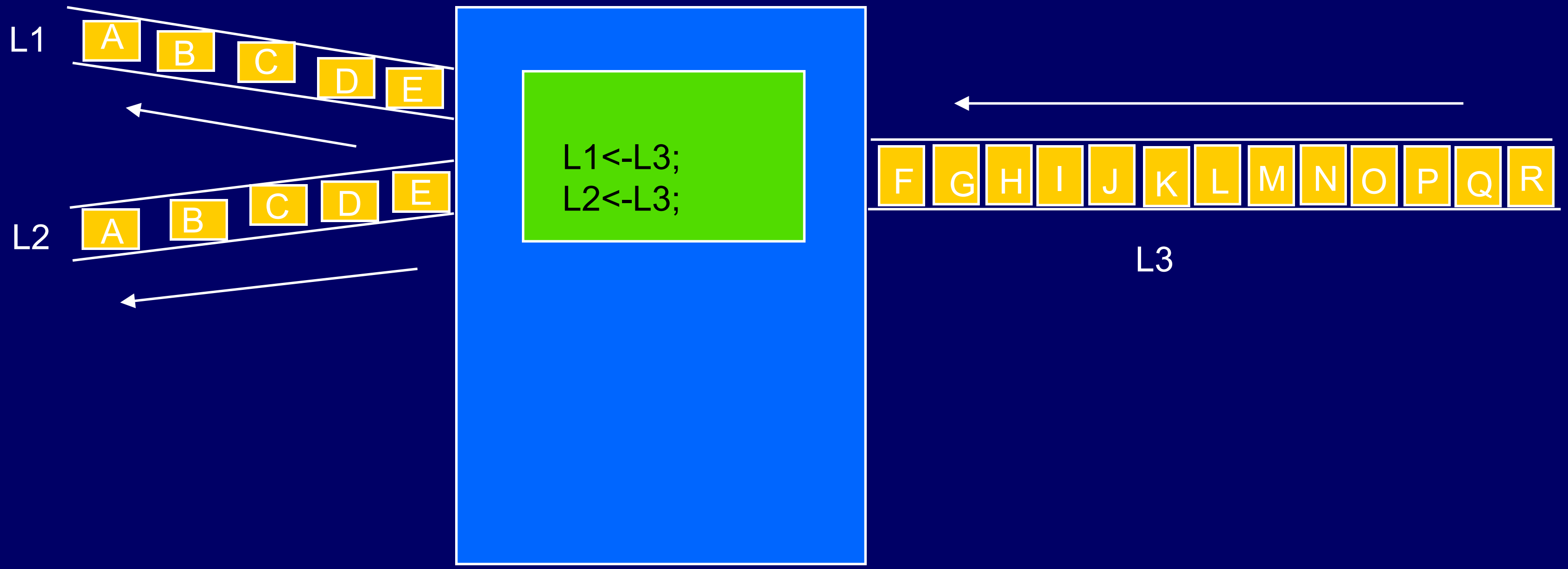
Resource Management, End-to-End

- Resource Management Challenges



Unsolved "gotchas": Local versus Global control

- Program copies L3 (in) to L1, L2 (out)



- Is this "Multicast" Program "safe"?

Can Active Packets trust the EE?

- "Reflections on Trusting Trust"
  - → Example of self-replicating compiler virus
  - → Lesson: You are *trusting* infrastructure!
- A.N. concern so far: trust of code
  - → Can the code trust the A.N.?
- Goal in an A.N.:
  - → Either operate in untrusted environments
  - → Or establish web of trust

Strategies for paranactive nets

- Carry *all* code with you in a capsule
  - → how do you load your code?
- Telescope out trust relationships with cryptography and identities
  - → need to think about *ad-hoc* relations
- Pre-establish trust relationships and verify at node

Result: E.E. in known state, *but…*

- Still trust some hardware
- Also trust repository for recovery
- Need *basis*, like diplomatic pouch containing a one-time pad
- A*pplications* aware AEGIS executed?
- Can *applications* know that system integrity has been *preserved?*

Some (maybe crazy) ideas:

- Allow paranactive applications to invoke AEGIS with themselves as target…
  - → Awful performance, poor multiplexing :-)
- Paranactive applications "disarm" *gradually* (gradually expose more code and credentials as environment is checked)
- Automated Trust Management (need new acronym - "third rail" of nets!)

Tutorial Outline:

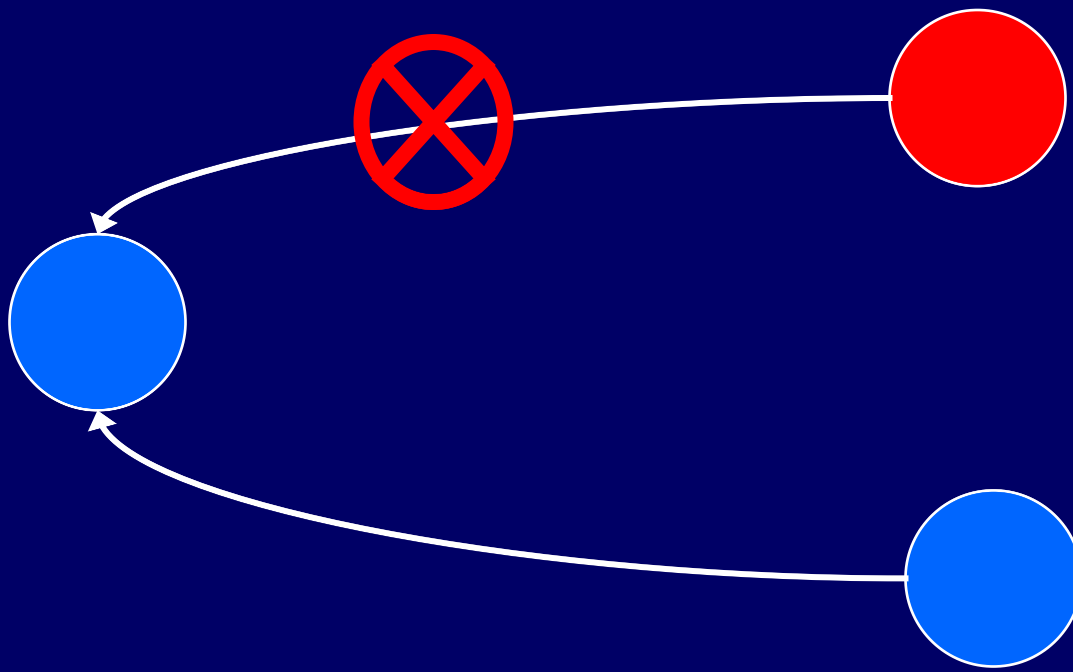
- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

3. The Secure Active Network Environment (SANE)

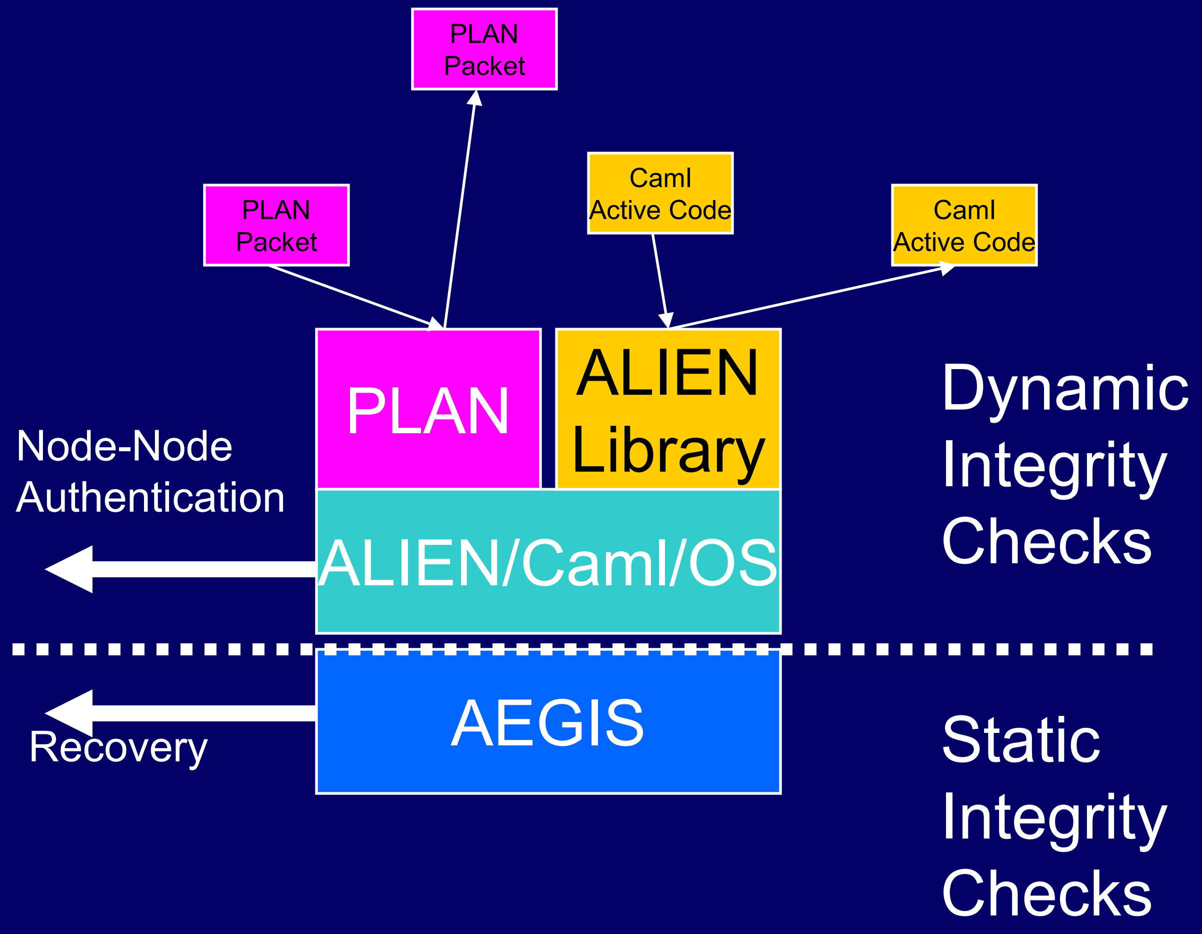
- Demonstrates active packet programming
- Mobile code authentication with cryptography
- Guarantees no corrupted component
- Allows recovery of failed components
- Enables trust relationships between nodes
- http://www.cis.upenn.edu/~waa
- http://www.cis.upenn.edu/~angelos

SANE Security Model

- Only process packets from trusted hosts

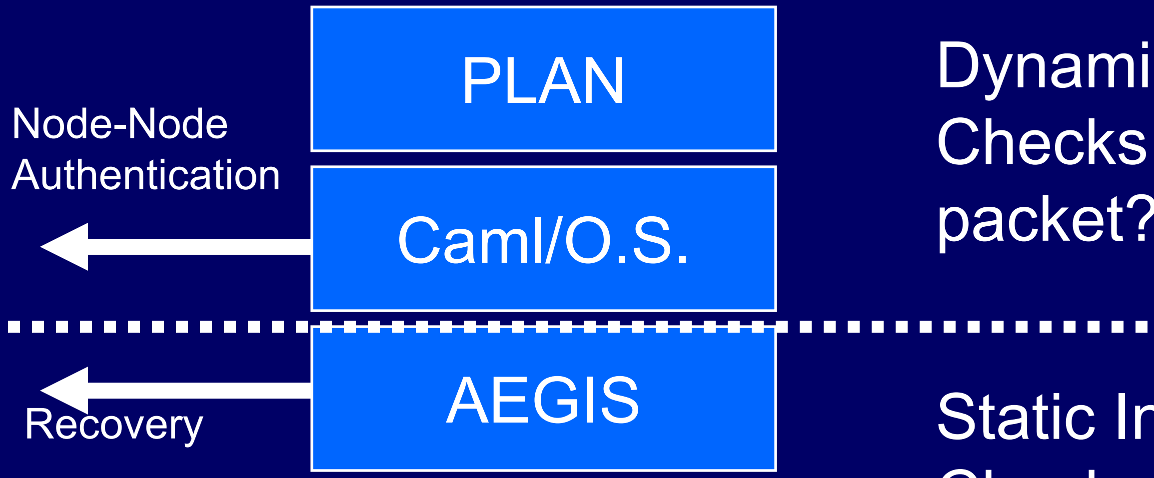


Example: SwitchWare Architecture



SANE Architecture

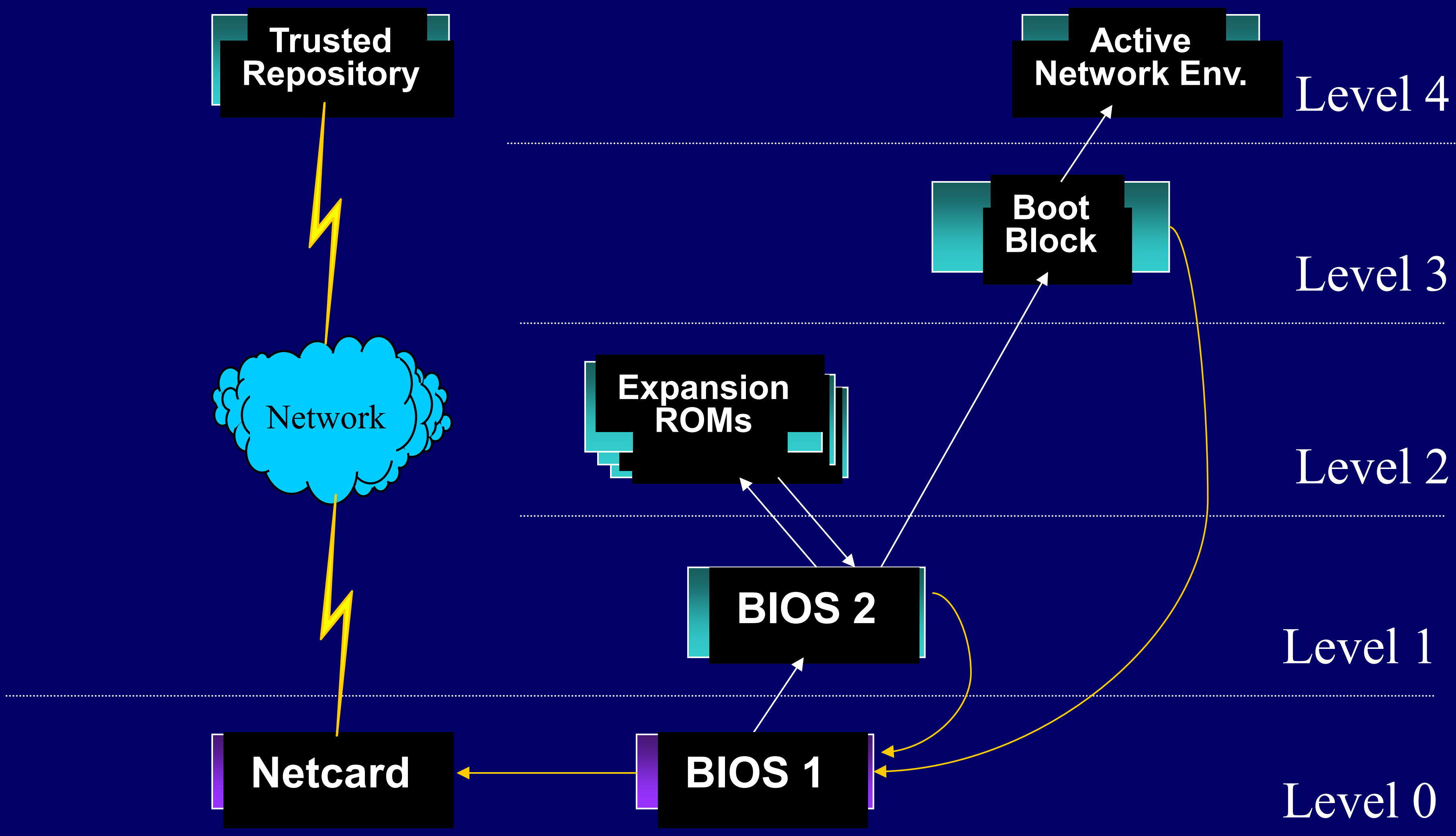
- "Trust, but Verify"



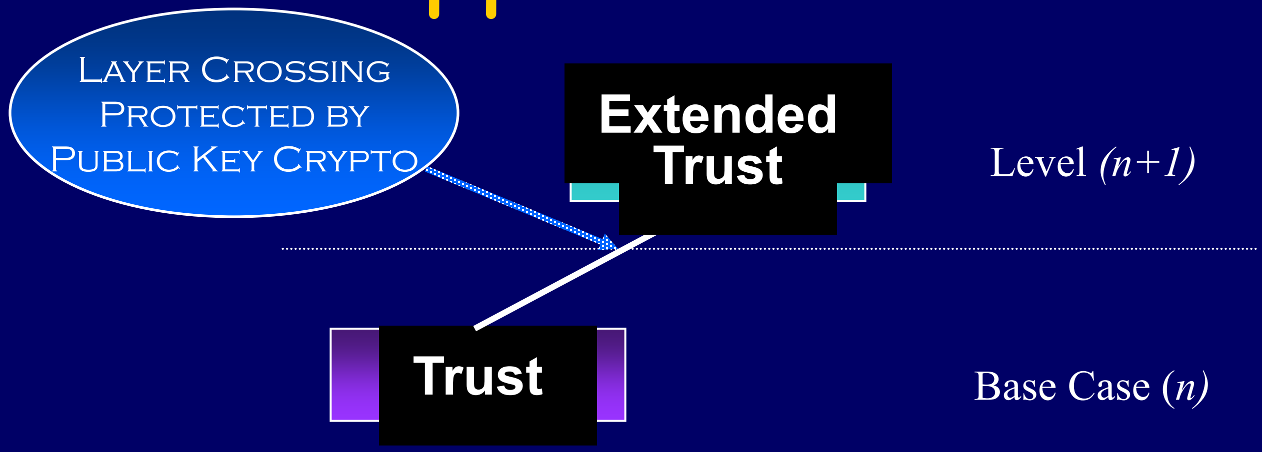
Dynamic Integrity Checks (Maybe per-packet?)

Static Integrity Checks (Done Once)

AEGIS Architecture

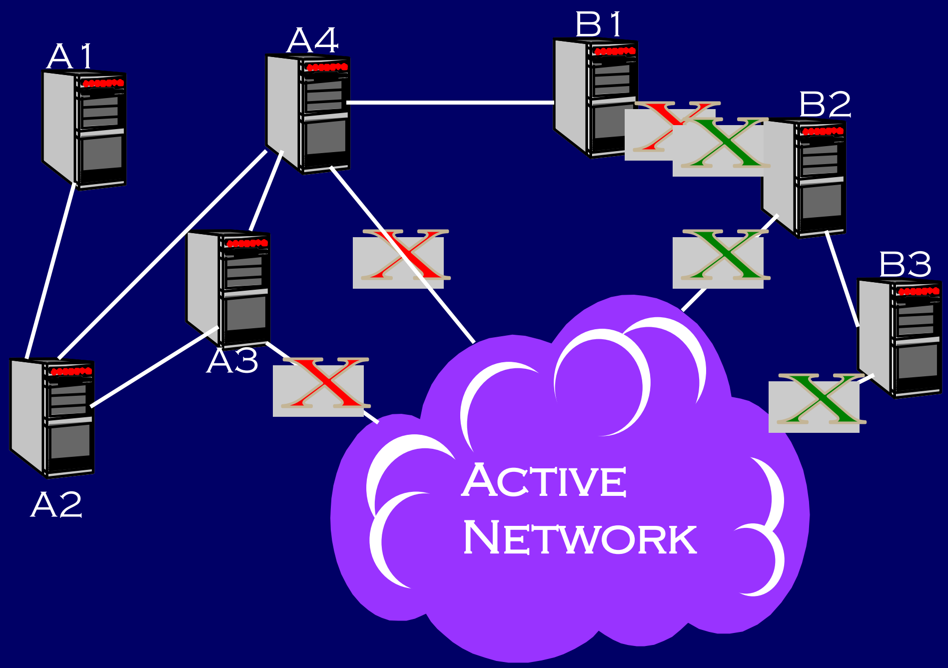


Approach



- Integrity and Trust Must be "*Grounded*" at the Lowest Possible Point.
- Chaining Layered Integrity Checks (CLIC) Extends Trust Beyond the Base Case.

Mutually Suspicious Nodes



- Nodes Authenticate their Neighbors
- Establish Trust Relations with Peers (PolicyMaker?)
- Use Trust Relations to Solve Existing Problems (eg. Routing)
- Optimize Authentication

Node to Node Authentication

- Once at Boot Time, Periodically Thereafter (Crypto "heartbeat")
- Modified Station-to-Station Protocol (Well Known and Understood)
- Key Can be Used to Authenticate on a Hop-by-Hop Basis, Encrypt Sensitive Information
- Make Traffic Analysis <u>Hard</u>

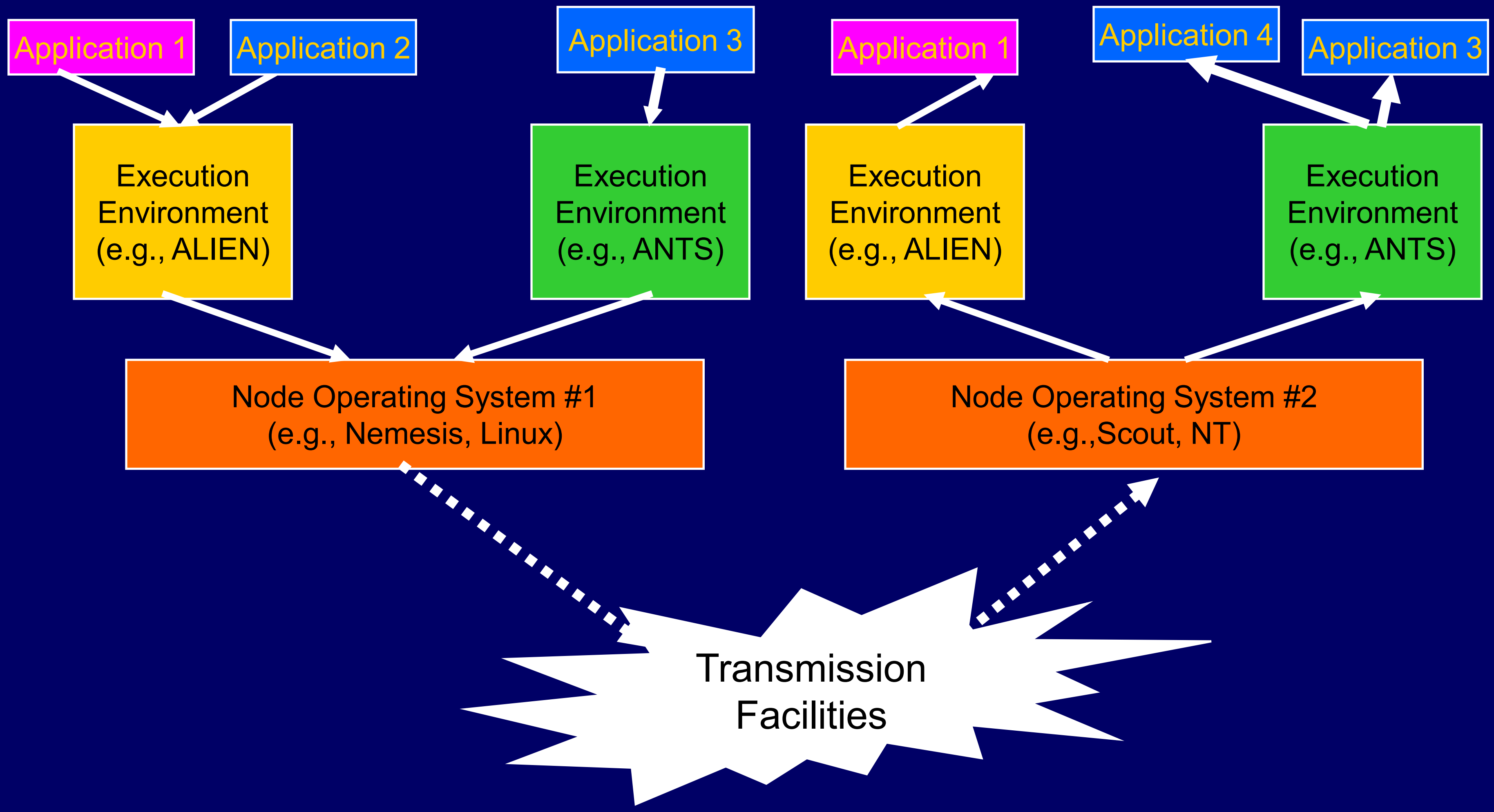
Tutorial Outline:

- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

4. Active Network Encapsulation Protocol (ANEP)

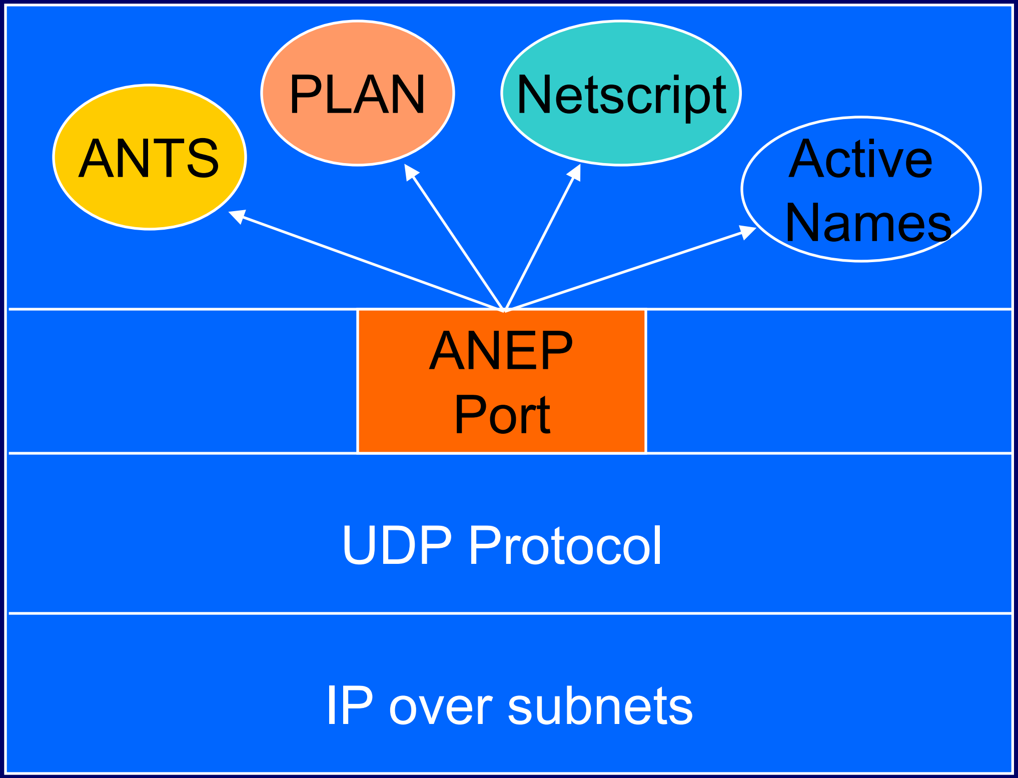
- Why ANEP?
- ANEP details
- Security features of ANEP

Internode Interoperation



ANEP demultiplexes to EEs

- Well-known UDP/IP Port for ANEP



ANEP Header Formaat

- Format of ANEP Header:

0	8	16	24
Version	Flags	Type ID	
ANEP Header Length		ANEP Packet Length	
Options			
Payload			

Terminology, FYI:

- *Packet*: ANEP Header + Payload
- *Active Node*: Network Element that can evaluate active packets
- *TLV*: Type/Length/Value triple
- *Basic Header*: First two words (8 octets) of the ANEP Header

ANEP Details: Fields

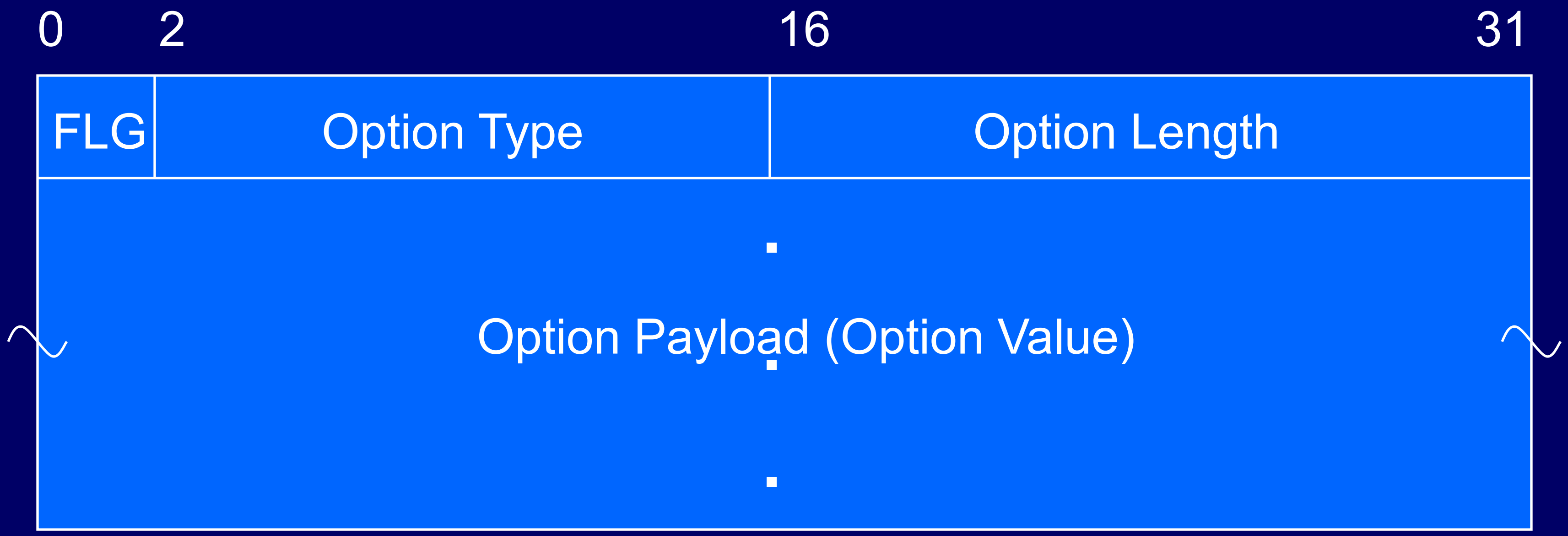
- *Version*: now 1; change w/ANEP header; discard if unknown value
- *Flags*: for V1, only MSB used
  - MSB=0, try to forward w/default
  - MSB=1, discard if TypeID not recognized
- *ANEP Header Length*: in 32 bit words
  - includes options; 2 if no options

Details: More fields...

- *TypeID*: evaluation environment for message; 16 bits; values by ANANA
  - → ANANA is currently Bob Braden
  - → Unrecognized value? Check *Flags* MSB
- *ANEP Packet Length*: Length of entire packet in *octets* (including payloads)
- *Options* length (variable) computed from Packet and Header length difference

Options

- Zero or more Type/Length/Value (TLV) constructs
- Follow the basic header. Format:

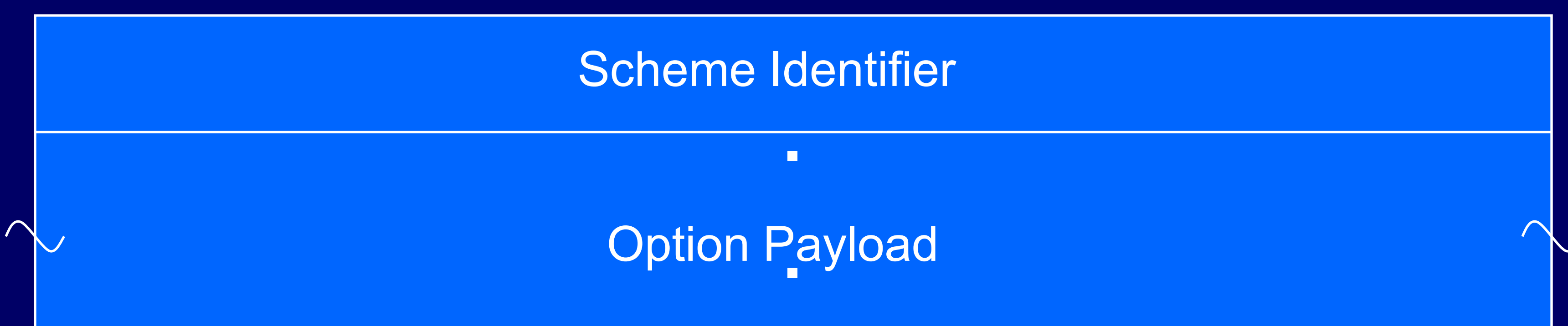


Option Fields

- *Option Type*: 14 bits, used to interpret *Option Payload*.
- Values assigned by ANANA; private when MSB of *FLG* is set.
- Unrecognized value? LSB of *FLG* 0, continue; 1 discard packet. Should log.
- *Option Length*: 16 bits; TLV length in 32 bit words; >= 1.

Option Type Values

- Reserved:
  - 1 - Source ID
  - 2 - Destination ID
  - 3 - Integrity Checksum
  - 4 - Non-Negotiated Authentication
- Format for Source, Destination, N-N:



Source Identifier

- Uniquely identifies sender
- *Scheme Identifier* is 32 bits; identifies addressing scheme to interpret the variable size *Option Payload*
- Reserved:
  - 1 - IPv4 Address (32 bits)
  - 2 - IPv6 Address (128 bits)
  - 3 - 802.3 Address (48 bits) (last two octets 0)

Destination Identifier

- Uniquely identifies destination in the active network
- Same payload option format as Source Identifier

Integrity Checksum

- Detect some packet integrity losses
- 16 bit 1's-complement of 1's-complement sum of the ANEP packet from the ANEP Version field
- Payload zero for computing checksum
- Option length field is <u>2.</u>

Non-Negotiated Authentication

- Provides 1-way authentication
- No prior negotiation assumed
- Option payload: 32 bit authentication scheme, followed by scheme's data.
- Option length field >2.
- Reserved:
  - 1 SPKI self-signed certificate
  - 2 X.509 self-signed certificate

Tutorial Outline:

- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

5. Case Study: ALIEN Active Loader

- Programming Language Approach
- Protection with "namespace sandbox"
- Extend to network with crypto
- Performance implications
- Not the whole story

Decisions in the Design Space

- Usability *vs.* Flexibility *vs.* Security *vs.* Performance
- A General-Purpose Language gets the first two for free; other two are <u>hard</u>!
- Domain-specific Languages (such as PLAN, Sec. 6 of tutorial) may achieve different tradeoffs

The ALIEN Approach

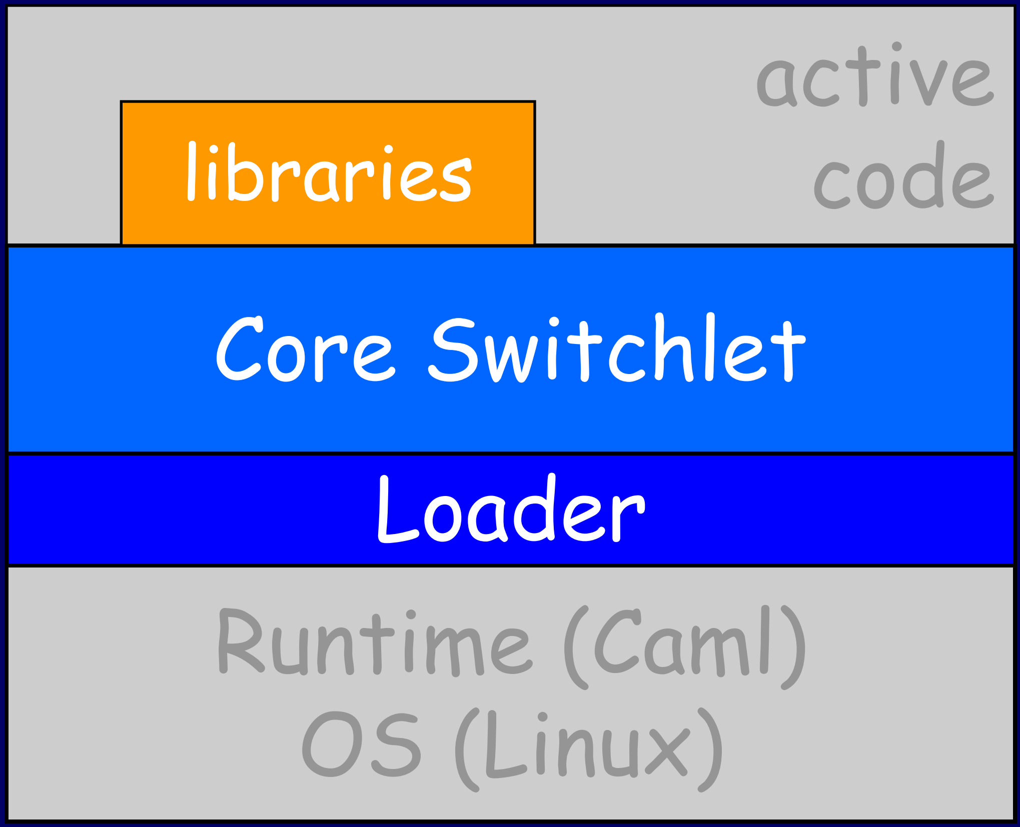
- Achieved by *restricting* a general computing model
- Realized in ALIEN, an active loader for Caml
  - → General computing model
  - → Interface to OS
  - → Interface to active code
- Only privileged portions of the system can directly access shared resources

The ALIEN Active Loader

- D. Scott Alexander
- CAML runtime
- CAML capsules restricted via module thinning
- Digitally-signed certificates for remote accesses to resources
- Will use for detailed case study

ALIEN in an Active Element

- Three layer architecture



Implementation of Active Code

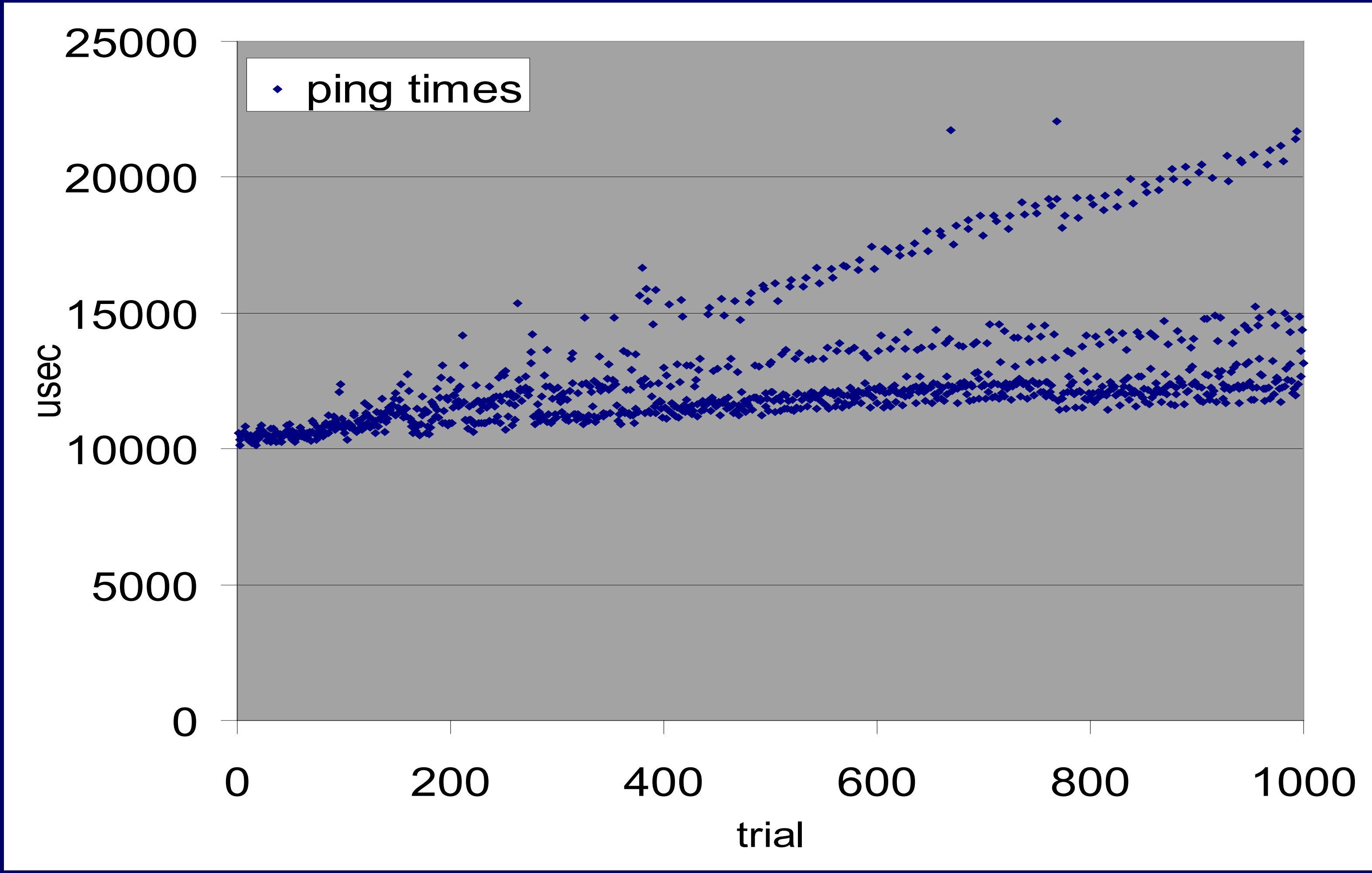
- Active Extensions
  - Loaded from disk or network (TFTP)
  - We use queues for communication
  - Could use upcalls...
    - Security?
  - ...or blocking downcalls
- Active Packets
  - ANEP encapsulated (over UDP or link layer)
  - Can use SANE for security
  - Linker/ procedure call for communications

Active Packets in ALIEN

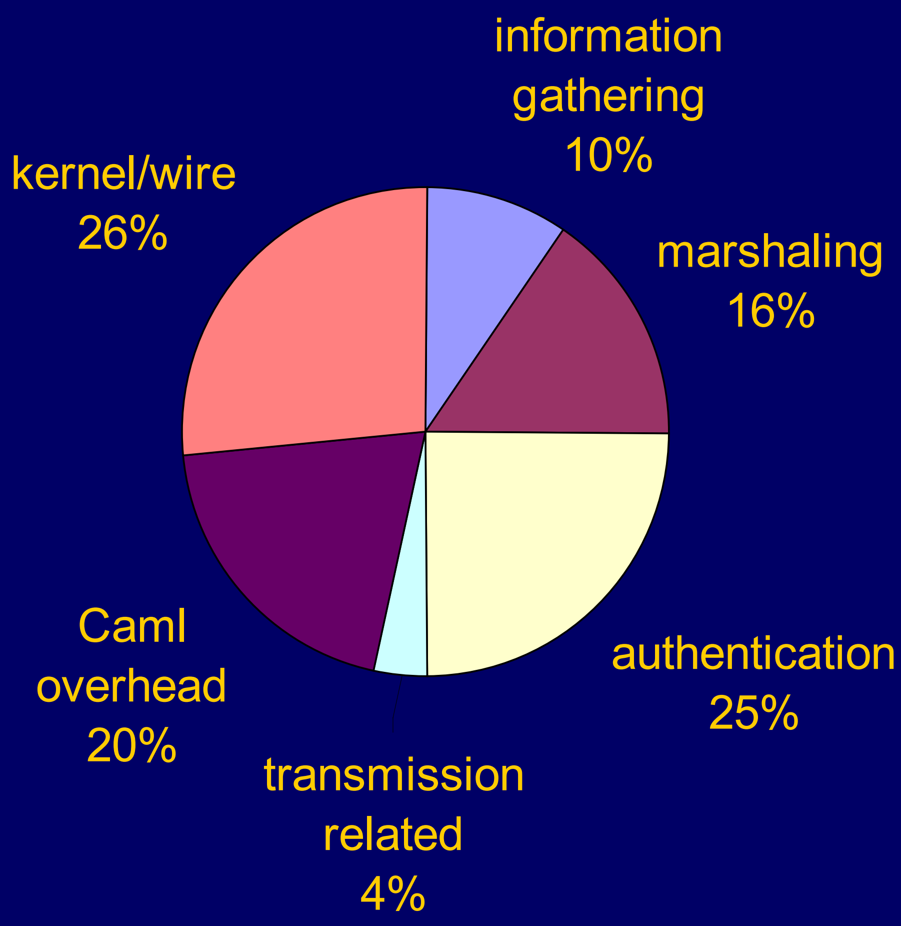
- If ANEP header indicates ALIEN
  - → SANE processing as part of ANEP
  - → Code portion is loaded
  - → *func* is called with code, data, and func name as arguments

link layer header	ANEP header/ SANE auth	code portion	data portion	func name

saneping Performance



Overall Breakdown of Costs



Major Costs

- Kernel/Wire (26%, 3078 μs)
  - Kernel time + transmission time
  - To avoid
    - Reduce size of packet
    - Reduce or avoid kernel boundary crossing cost
- Authentication (25%, 2910 μs)
  - Mostly cost of performing SHA-1 (4 times)

Cryptography is Expensive

- Implemented in C because too slow in Caml
- Times to hash 4MB of data

	bytecode	native
Caml Int32	86.45s	61.99s
Caml int	36.03s	2.48s
C		0.33s

The take-home lesson:

- Must reduce per-packet crypto costs:
  - → Active extension amortizes costs
  - → ANTS caching amortizes costs
  - → Smaller packets (Dense CISC, a la BBN)
- Or, find another way to avoid crypto in the common case…

Tutorial Outline:

- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

6. PLAN, RCANE, STRONGMAN

- PLAN
- RCANE
- STRONGMAN

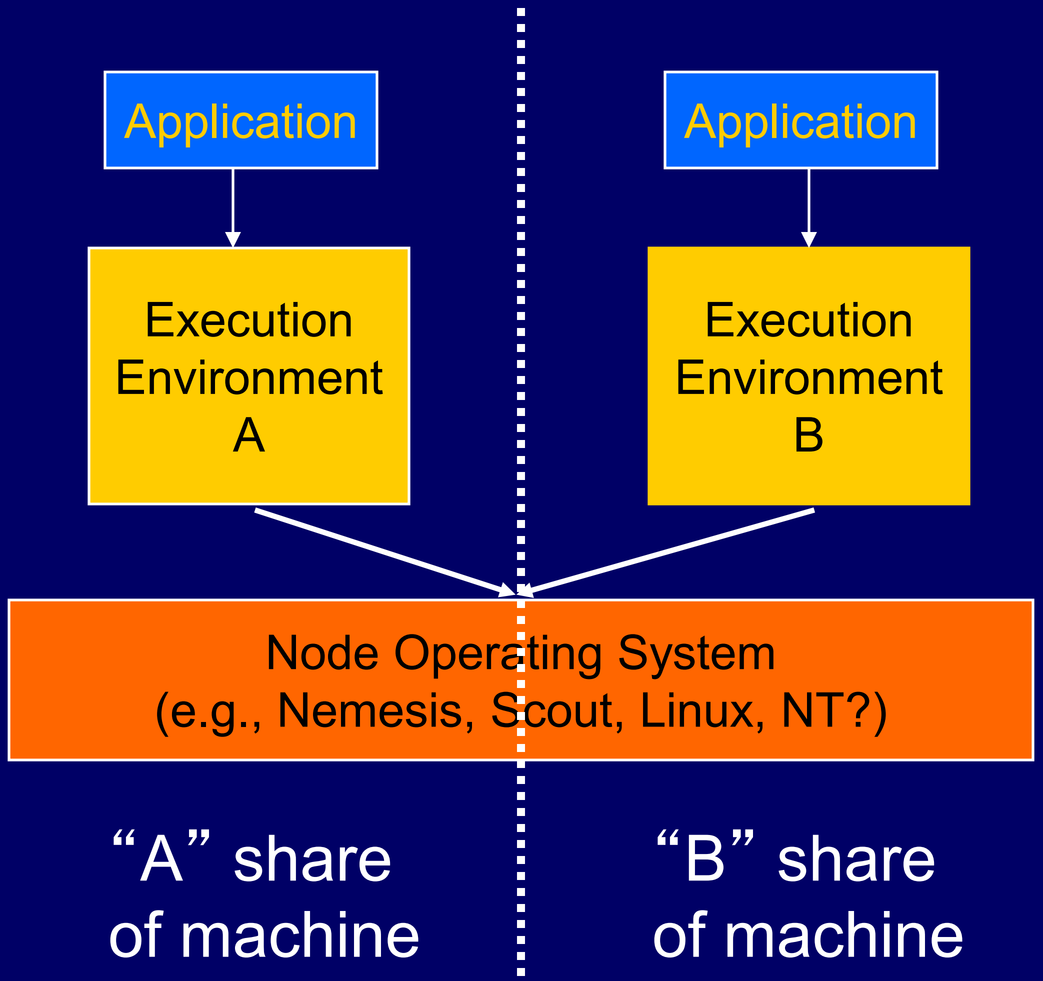
Packet Language for Active Networks (PLAN)

- Hicks, Kakkar, Moore, Gunter, Nettles
- Capsule-based approach
- CAML runtime
- Highly-restricted domain specific language (a safe “glue” language, like the UNIX shell), extensible via ALIEN
- Active extensions do restricted things

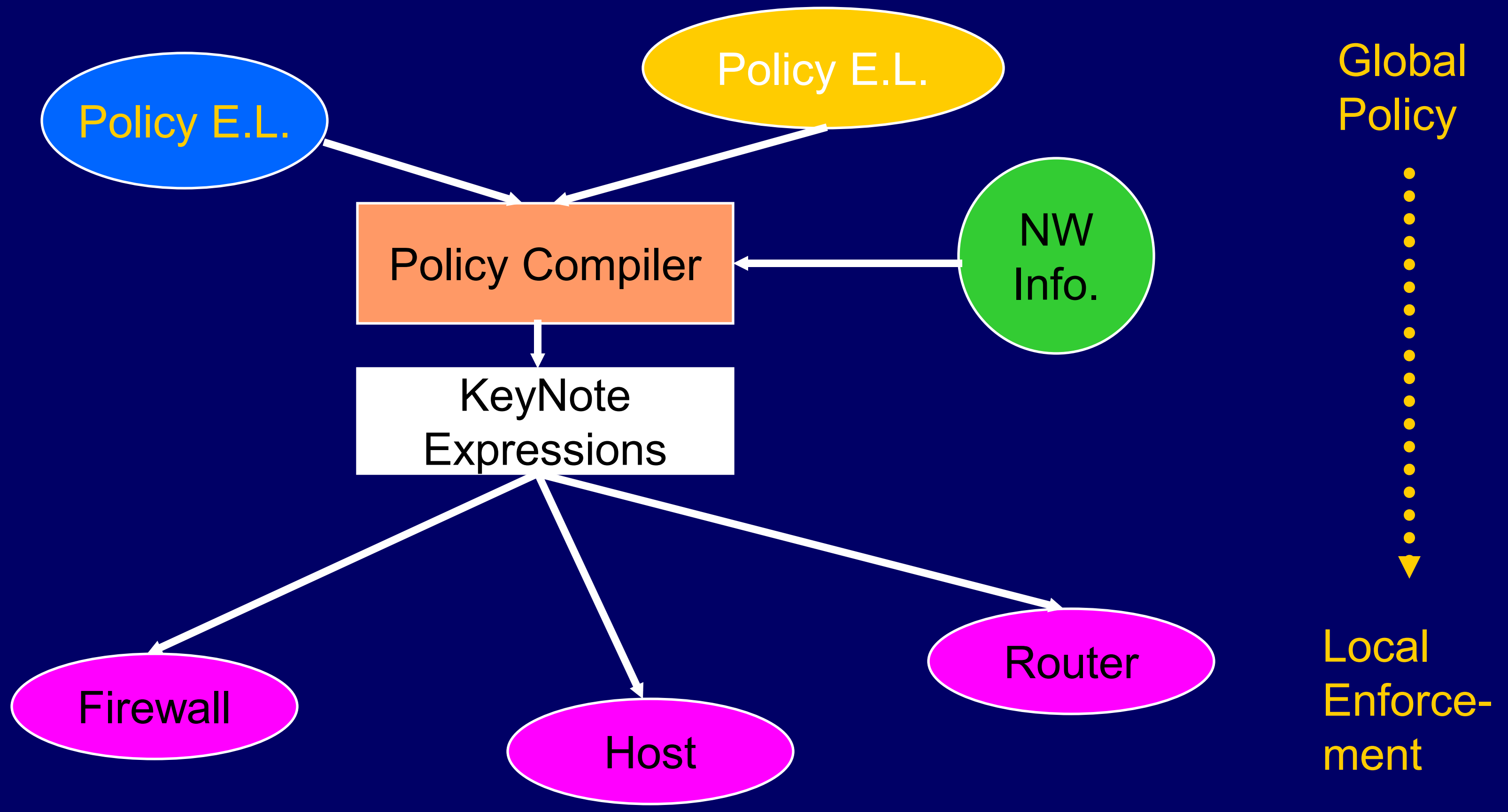
Resource Controlled Active Network Element (RCANE)

- Manage CPU, Memory and Bandwidth
  - → Challenge: Modern PL heaps (GC)
  - → Challenge: Interrupts
  - → Challenge: CPU/Mem/BW tradeoffs
- Approach
  - → Experimental RCANE with Cambridge (UK) using Nemesis O.S. for NodeOS and SwitchWare E.E.; NSF-funded at Penn; see IWAN talk by Paul Menage of Cambridge

RCANE Vertical Architecture:



STRONGMAN Architecture



STRONGMAN

- Penn / AT&T Research
- Logical "meta-KeyNote"
- High-level *policy* compiles to KeyNote
- Policy-based configuration of *groups* of security endpoints (firewalls, hosts, routers, ...)
- Multiple *policy expression languages* compile to common KeyNote policy model

Describing Actions in KeyNote

- <Attribute,Value> **Action Environment**

$filename	"/home/stan/foo"
$owner	"stan"
$hostname	"lake.sp.co.us"

- Attribute semantics application-specific
- An Action always associated w/Requestor

KeyNote Example

- Authorizer: *stan's public key*
- Licensees: *wendy's public key*
- Conditions: $file_owner == "stan"
  && $filename ~= "/home/stan/[^/]*"
  -> "true";
- Signature: stan's signature

Tutorial Outline:

- Introduction to Active Networks
- Security
- Secure Active Network Environment
- Active Network Encapsulation Protocol
- Case Study: ALIEN Active Loader
- PLAN, RCANE and STRONGMAN
- Status and a 2020 Vision

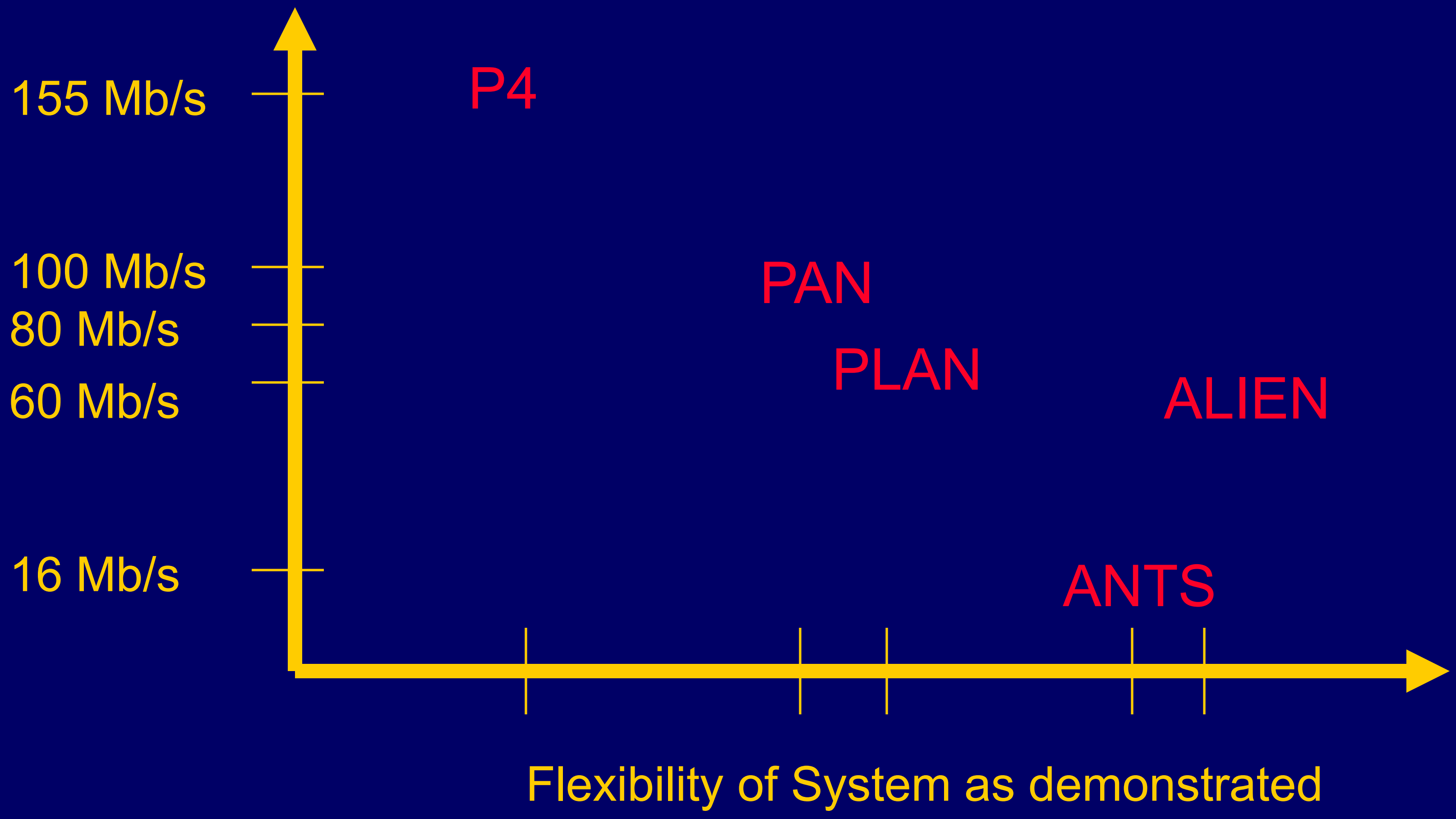
7. Summary and a 2020 Vision

- Myths
- Reality
- Five years out
- Twenty years out - 2020

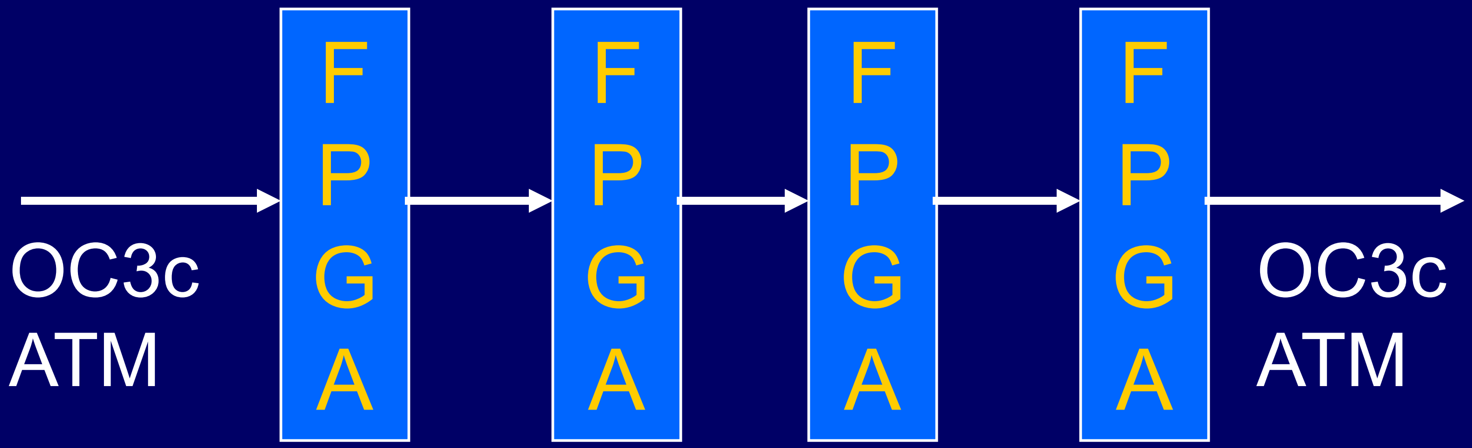
Three Big Myths

- Active Networks will not perform well
- Active Networks cannot be secured
- Active Networks are an increment on current thinking

Some Performance Tradeoffs



The Programmable Protocol Processing Pipeline (P4)

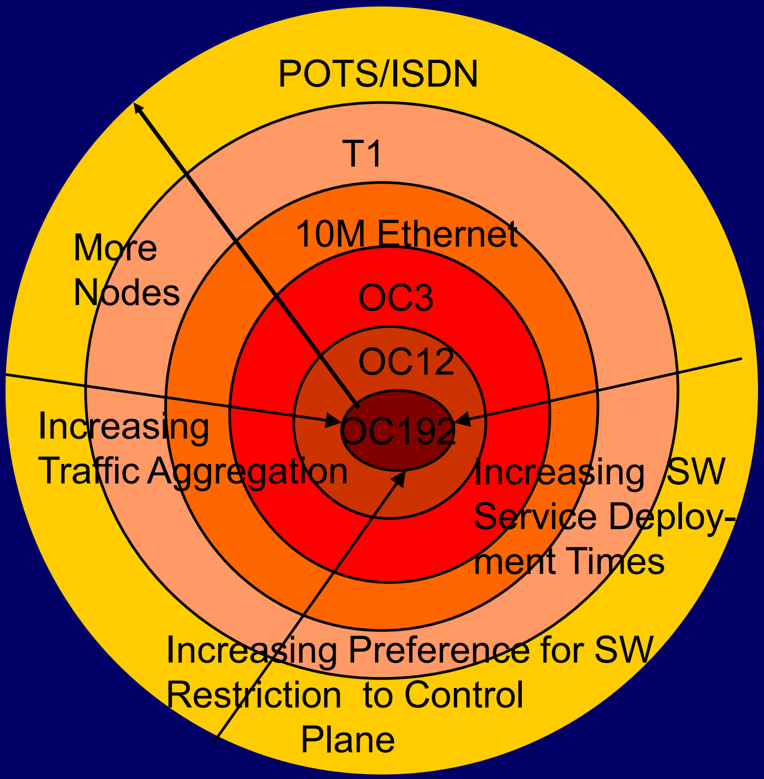


http://www.cis.upenn.edu/~boosters

The P4 illustrates

- A restricted programming environment
  - →Field-programmable gate arrays
- Very high performance; operates at OC-3c line rate with a 19.44Mhz clock
- Easily reaches to 300-400 Mbps with increases in clock rate and word size
- Can be integrated with software EE
  - →A high-performance active HW/SW *hybrid*

Activation potential at various commercially deployed rates:



Take-Home Lesson Number 1:

- Access points are 14.4-10Mbps
- Peering Points are 1.5Mbps-155Mbps
- Almost all are near the slow ends
- Active Network *Prototypes* cover the entire range!
- This is probably the most sensible place to put value-added services in any case

Security - not *entirely* there…

- ANTS uses MD5 hashes of programs to identify them at each active node
  - → Namespace isolation
  - → ANTS "virtual machines"
- ALIEN Active Loader
  - → Namespace control with "module thinning"
  - → Extend to net with cryptography (at some performance cost)

But no worse than the Internet…

- Secure Active Network Environment
  - → AEGIS Secure Bootstrap (EE integrity)
  - → Node-node authentication
- Packet Language for Active Networks
  - → Restricted "safe" base PLAN language
  - → Controlled Access to Active Extensions

And long-term, possibly better!

- Resource Controlled Active Net Environment (RCANE)
  - EEs/Caml on Nemesis => RCANE
  - Thwarts Denial-of-Service
- Research Underway to Specify Global Policy and translate to Local Actions
  - STRONGMAN trust management compiler
  - Netscript global firewalls

Take-Home Lesson Number 2:

- Greater complexity of AN architecture, and programmability, inspires fear
- But it also stimulates *designed-in* security
- AEGIS and RCANE provide more broadly applicable results
- Programmability: from *nodes* to *nets!*

Physics and Networks

- Speed of light limits propagation delay
- Bandwidth is increasing exponentially, and therefore bandwidth*delay
- How do we control networks?
  - → Round-trip time paced control?
- Require network-embedded control!

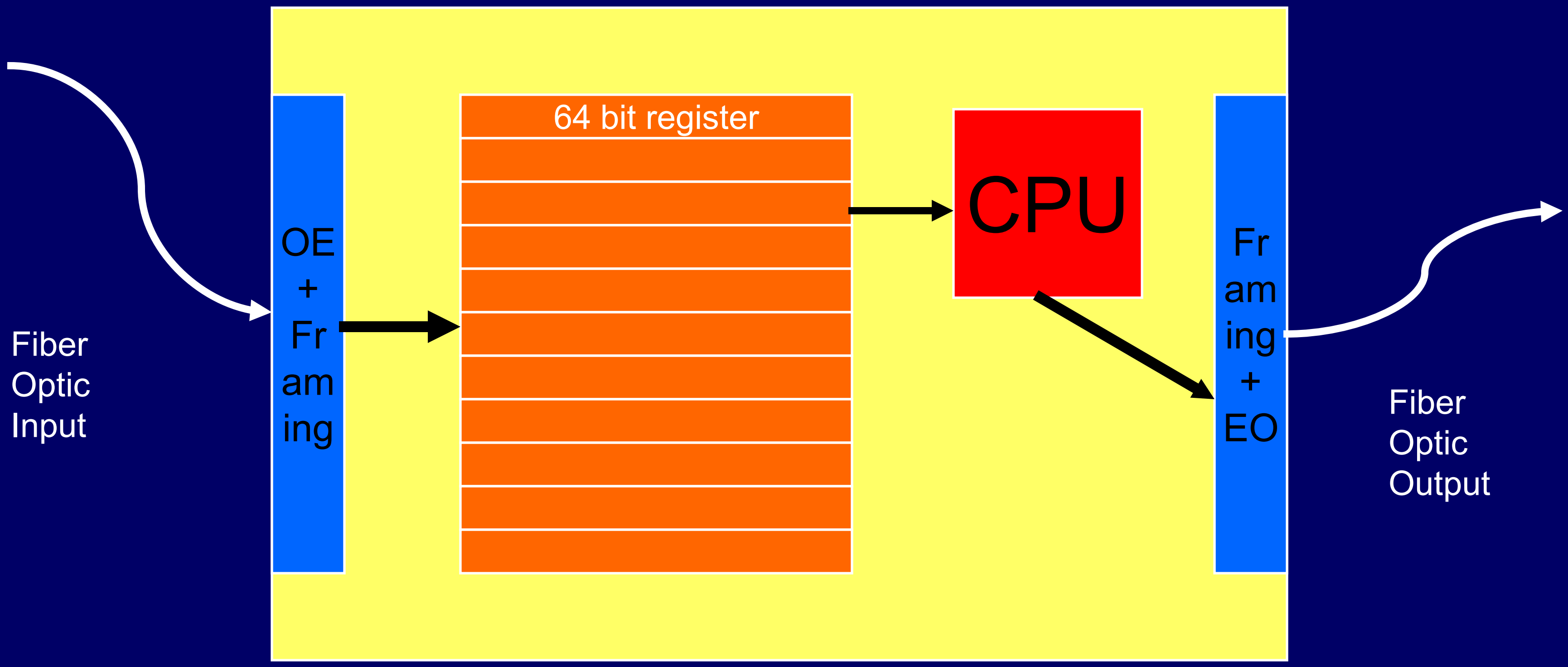
Take Home Lesson #3,……

- This isn’t about improving TCP 0.0001%
- This isn’t about selecting header fields
- It’s about integrating networks and computing in a seamless and useful way!

Three Big Truths

- Active Networks perform well
- Active Networks can be secured
- Active Networks will help address the problems of the future; think big - the past is already coded!

2005: in-Fiber processing?



Register-Only Media Processor (ROMP)

Human I/O architecture

- High-bandwidth video input
  - → feeds slow symbol processor (Card, et al)
  - → asymmetric - no fast video out!
- Audio input/output (100 kilobits/sec)
- Other senses (touch, smell, taste…)
- The asymmetry is HUGE (10-1000)
- Lots of intermediate filtering

Technology echoes biology…

- Newspapers
  - →Many readers, few writers
- Television
  - →Video out, remote control in
- Web
  - →Video, etc. out, text/clicks in
- Coupled to I/O architecture!

Biology and Networks

- We can probably handle 50 Mbps input
- Is that all we need? No!
- Want to find best of 10,000,000 video streams occurring simultaneously
  - → finding
  - → selecting
  - → focus
- Network as Information Appliance!

Optimally

- Information flows in audio/video
- Information flows out audio (speech recognition *should* be faster than keyboarding!)
- Information systems get the “best” (necessary, relevant, etc.) information to the presentation point (eyes, ears)

The “2020 Vision”

- Is (# people)*(video bit rate) all the bandwidth we will ever need?
- NO! There’s a lot going on!
- The “vision” is one of *information fusion*
- The goal is: right information, to right person, at the right time
- Huge challenges in systems design

The basic architecture

- Nets and computers improving exponentially. Humans, well…
- Active nodes have "delegates"
  - →select information (watching a million cameras……)
  - →forward towards you for consumption
  - →your senses extended into the network

Can we do it?

- Active nets are getting there
  - →architecture being developed
  - →performance, security, scale all issues
  - →mature in 2-5 years
- We need deployable HCI and AI technologies
- Towards the ultimate SPAM filter!

Acknowledgments:

- All Penn work and most other work supported by DARPA ITO.
- Collaborators: Alexander, Arbaugh, Farber, Feldmeier, Gunter, Hadzic, Hicks, Keromytis, Marcus, McAuley, Menage, Moore, Nettles, Segal and Sincoskie...
- Hewlett-Packard, Intel and 3Com