OS Security

COMP9242 – Advanced OS

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(with thanks to Gernot Heiser, from whom some of this material is borrowed)

Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

NICTA Funding and Supporting Members and Partners

INTRODUCTION

What is security?

- Different things to different people:

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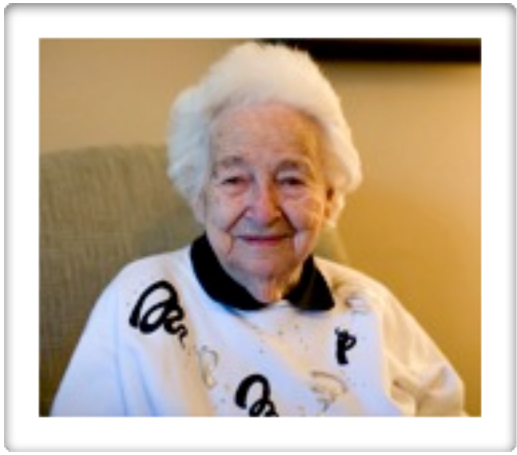

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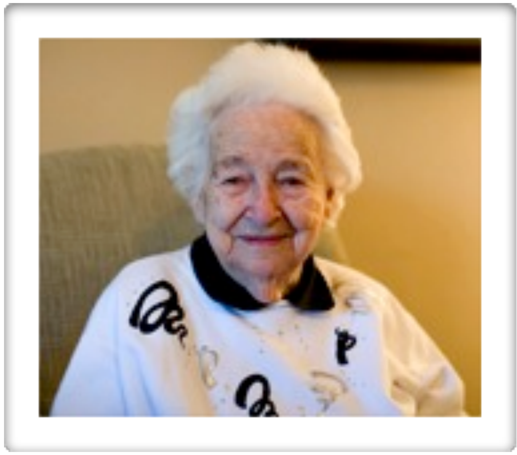

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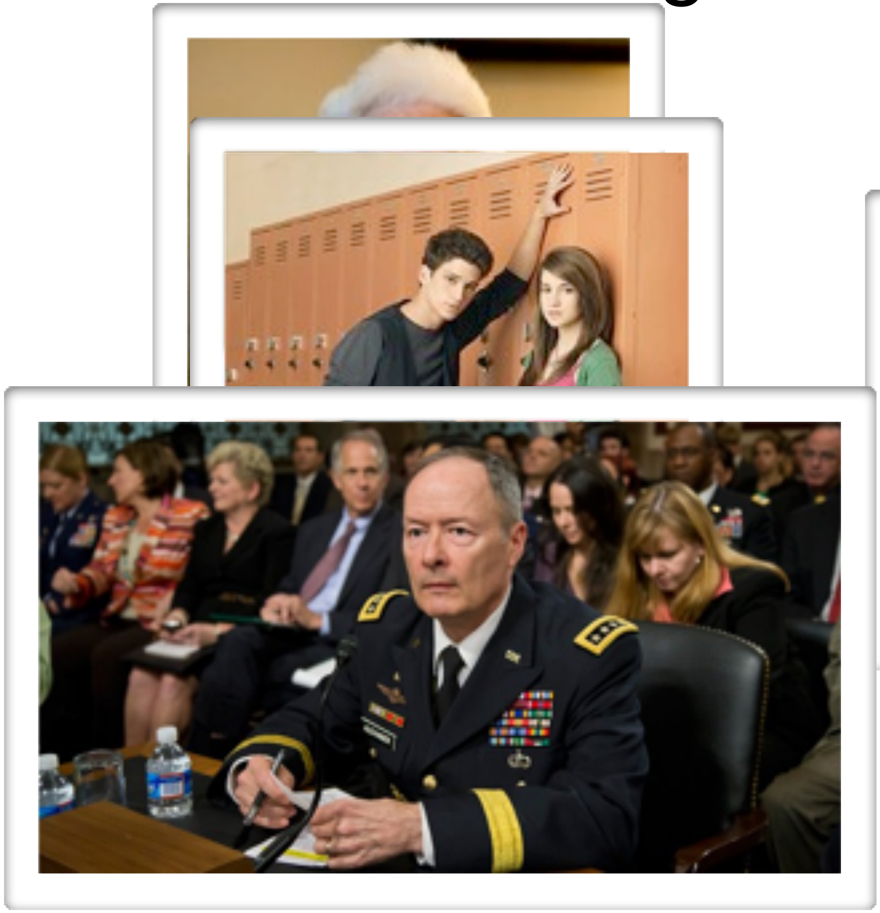


What is security?

- Different things to different people:

I stalk
2002-2009
Tracking GhostNet:
Investigating a Cyber Espionage Network
Information Warfare Monitor
March 29, 2009

What is security?

- Different things to different people:

Computer Security

- Protecting **my** interests that are under computer control from malign threats
- Inherently subjective
  - Different people have different interests
  - Different people face different threats
- Don't expect one-size-fits-all solutions
  - Grandma doesn't need an air gap
  - Windows alone is insufficient for protecting TOP SECRET classified data
    - on an Internet-connected machine

State of OS Security

- Traditionally:
  - Has not kept pace with evolving user demographics
    - Focused on e.g. Defence and Enterprise
  - Has not kept pace with evolving threats
    - Focused on protecting users from other users, not from the programs they run
- Is getting better
  - But is hindered because:
    - We don’t yet understand how to write secure code
    - OSes are getting larger and more complex

OS Security

- What is the role of the OS for security?
- Minimum:
  - provide **mechanisms** to allow the construction of secure systems
  - that are capable of securely implementing the intended users'/administrators' **policies**
  - while ensuring these mechanisms cannot be subverted

Good security mechanisms

- Are widely applicable
- Support general security principles
- Are easy to use correctly and securely
- Do not hinder non-security priorities (e.g. productivity, generativity)
- Lend themselves to correct implementation and verification

Security Design Principles

- Saltzer+Schroeder (SOSP ’73, CACM ’74)
  - Economy of mechanism
  - Fail-safe defaults
  - Complete mediation
  - Open design
  - Separation of privilege
  - Least privilege
  - Least common mechanism
  - Psychological acceptability

Common OS Security Mechanisms

- Access Control Systems
  - control what each process can access
- Authentication Systems
  - confirm the identity on whose behalf a process is running
- Logging
  - for audit, detection, forensics and recovery
- Filesystem Encryption
- Credential Management
- Automatic Updates

Security Policies

- Define what should be protected
  - and from whom
- Often in terms of common security goals:
  - **Confidentiality**
    - X should not be learnt by Y
  - **Integrity**
    - X should not be tampered with by Y
  - **Availability**
    - X should not be made unavailable to Z by Y

Policy vs. Mechanism

- Policies accompany mechanisms:
  - **access control** policy
    - who can access what?
  - **authentication** policy
    - is password sufficient to authenticate TS access?
- Policy often restricts the applicable mechanisms
- One person’s policy is another’s mechanism

Assumptions

- All policies and mechanisms operate under certain **assumptions**
  - **e.g.** TS cleared users can be trusted not to write TS data into the UNCLASS window
- Problem: implicit or poorly understood assumptions
- Good assumptions:
  - clearly identified
  - verifiable

Risk Management

- Comes down to **risk management**
  - At the heart of all security
  - Assumptions: risks we are willing to tolerate
- Other risks:
  - we mitigate (using security mechanisms)
  - or transfer (e.g. by buying insurance)
- Security policy should distinguish which is appropriate for each risk
  - Based on a thorough **risk assessment**

Trust

- Systems always have **trusted** entites
  - whose misbehaviour can cause insecurity
  - hardware, OS, sysadmin ...
- **Trusted Computing Base** (TCB):
  - the set of all such entities
- Secure systems require **trustworthy** TCBs
  - achieved through assurance and verification
  - shows that the TCB is unlikely to misbehave
  - why the TCB should be as small as possible

Assurance and Formal Verification

- **Assurance**:
  - systematic evaluation and testing
- **Formal verification**:
  - mathematical proof
- Together trying to establish correctness of:
  - the **design** of the mechanisms
  - and their **implementation**
- **Certification**: establishes that the assurance or verification was done right

Covert Channels

- Information flow not controlled by security mechanism
  - confidentiality requires absence of all such
- Covert **Storage** Channel:
  - attribute of shared resource used as channel
  - controllable by access control
- Covert **Timing** Channel:
  - temporal order of shared resource accesses
  - outside of access control system
  - much more difficult to control and analyse

Covert Timing Channels

- Created by shared resource whose timing-related behaviour can be monitored
  - network bandwidth, CPU load ...
- Requires access to a time source
  - anything that allows processes to synchronise
- Critical issue is channel bandwidth
  - low bandwidth limits damage
    - why DRM ignores low bandwidth channels
  - beware of amplification
    - e.g. leaking passwords, encryption keys etc.

Summary: Introduction

- Security is very subjective
- OS security:
  - provide good security **mechanisms**
  - that support users' **policies**
- Security depends on establishing **trustworthiness** of trusted entities
  - **TCB:** set of all such entities
    - should be as small as possible
  - Main approaches: assurance and verification
- The OS is necessarily part of the TCB

ACCESS CONTROL PRINCIPLES

Access Control

- **who** can access **what** in which ways
  - the "who" are called **subjects**
    - e.g. users, processes etc.
  - the "what" are called **objects**
    - e.g. individual files, sockets, processes etc.
    - includes all subjects
  - the "ways" are called **permissions**
    - e.g. read, write, execute etc.
    - are usually specific to each kind of object
    - include those meta-permissions that allow modification of the protection state
      - e.g. own

AC Mechanisms and Policies

- AC Policy
  - Specifies allowed accesses
  - And how these can change over time
- AC Mechanism
  - Implements the policy
- Certain mechanisms lend themselves to certain kinds of policies
  - Certain policies cannot be expressed using certain mechanisms

Protection State

- **Access control matrix** defines the **protection state** at any instant in time

	Obj1	Obj2	Obj3	Subj2
Subj1	R	RW		send
Subj2		RX		control
Subj3	RW		RWX own	recv

Storing Protection State

- Not usually as access control matrix
  - – too sparse, inefficient
- Two obvious choices:
  - – store individual columns with each object
    - defines the subjects that can access each object
    - each such column is called the object's **access control list**
  - – store individual rows with each subject
    - defines the objects each subject can access
    - each such is called the subject's **capability list**

Access Control Lists (ACLs)

- Subjects usually aggregated into classes
  - e.g. UNIX: owner, group, everyone
- Meta-permissions (e.g. own)
  - control class membership
  - allow modifying the ACL
- Implemented in almost all commercial OSes

	Obj1
Subj1	R
Subj2	
Subj3	RW

Capabilities

- A **capability** is a capability list element

	Obj1	Obj2	Obj3	Subj2
Subj1	R	RW		send

  - **Names** an object to which the capability refers
  - **Confers** permissions over that object
- Less common in commercial systems
  - More common in research though

Capabilities: Implementations

- Capabilities must be unforgeable
- On conventional hardware, either:
  - Stored as ordinary user-level data, but unguessable due to sparseness
    - like a password or an encryption key
  - Stored separately (in-kernel), referred to by user programs by index/address
    - like UNIX file descriptors
- Sparse capabilities can be leaked more easily, but are easier to revoke
  - The only solution for most distributed systems

ACLs and Capabilities: Duals?

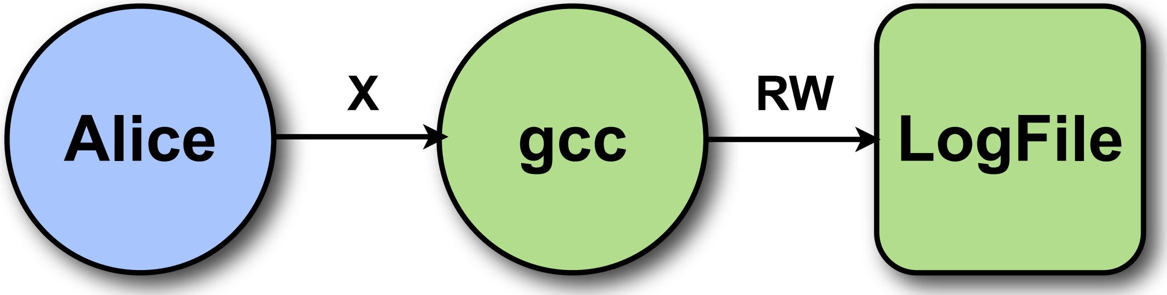
- In theory:
  - Dual representations of access control matrix
- Practical differences:
  - Naming and namespaces
    - Confused Deputies
  - Evolution of protection state
  - Forking
  - Auditing of protection state

Duals: Naming and Namespaces

- ACLs:
  - objects referenced by **name**
    - e.g. open("/etc/passwd",O_RDONLY)
  - require a subject (class) namespace
    - e.g. UNIX users and groups
- Capabilities:
  - objects referenced by **capability**
    - object namespace still required though
  - no subject namespace required

Duals: Confused Deputies

- ACLs: separation of object naming and permission can lead to confused deputies
  - Capabilities are both names and permissions
    - You can't name something without having permission to it



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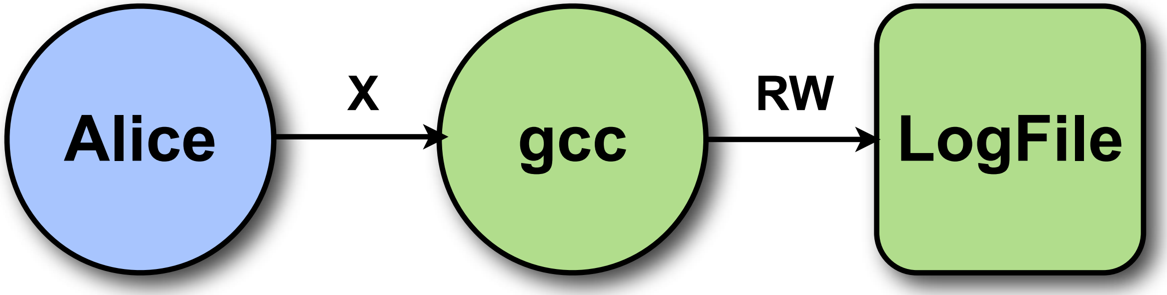


exec “gcc” “-o LogFile”

Duals: Evolution of Protection State

- ACLs:
  - Protection state changes by modifying ACLs
    - Requires certain meta-permissions on the ACL
- Capabilities:
  - Protection state changes by delegating and revoking capabilities
    - Right to delegate controlled by certain capabilities
    - e.g. A can delegate to B only if A has a capability to B that carries appropriate permissions

Duals: Forking

- What permissions should children get?
- ACLs: depends on the child's subject
  - UNIX etc.: child inherits parent's subject
    - Inherits **all** of the parent's permissions
    - Any program you run inherits all of your authority
  - Bad for least privilege
- Capabilities: child has no caps by default
  - Parent gets a capability to the child upon fork
  - Used to delegate (only) necessary authority
  - Much better for least privilege

Duals: Auditing of Protection State

- How to work out who has permission to access a particular object (right now)?
  - – ACLs: Just look at the ACL
- How to work out what objects a particular subject can access (right now)?
  - – Capabilities: Just look at its capabilities
- "Who can access my stuff?" vs. "How much damage can this thing do?"

Mandatory vs. Discretionary AC

- Discretionary Access Control:
  - Users can make access control decisions
    - delegate their access to other users etc.
- Mandatory Access Control (MAC):
  - enforcement of administrator-defined policy
  - users cannot make access control decisions (except those allowed by mandatory policy)
  - can prevent untrusted applications running with user's privileges from causing damage

MAC

- Common in areas with global security requirements
  - e.g. national security classifications
- Less useful for general-purpose settings:
  - hard to support different kinds of policies
  - all policy changes must go through sysadmin
  - hard to dynamically delegate only specific rights required at runtime

Bell-LaPadula (BLP) Model

- MAC Policy/Mechanism
  - Formalises National Security Classifications
- Every object assigned a **classification**
  - e.g. TS, S, C, U
- Classifications ordered in a **lattice**
  - e.g. TS > S > C > U
- Every subject assigned a **clearance**
  - Highest classification they're allowed to learn

BLP: Rules

- Simple Security Property ("no read up"):
  - s can read o iff clearance(s) >= class(o)
  - S-cleared subject can read U,C,S but not TS
  - standard confidentiality
- *-Property ("no write down"):
  - s can write o iff clearance(s) <= class(o)
  - S-cleared subject can write TS,S, but not C,U
  - to prevent accidental or malicious leakage of data to lower levels

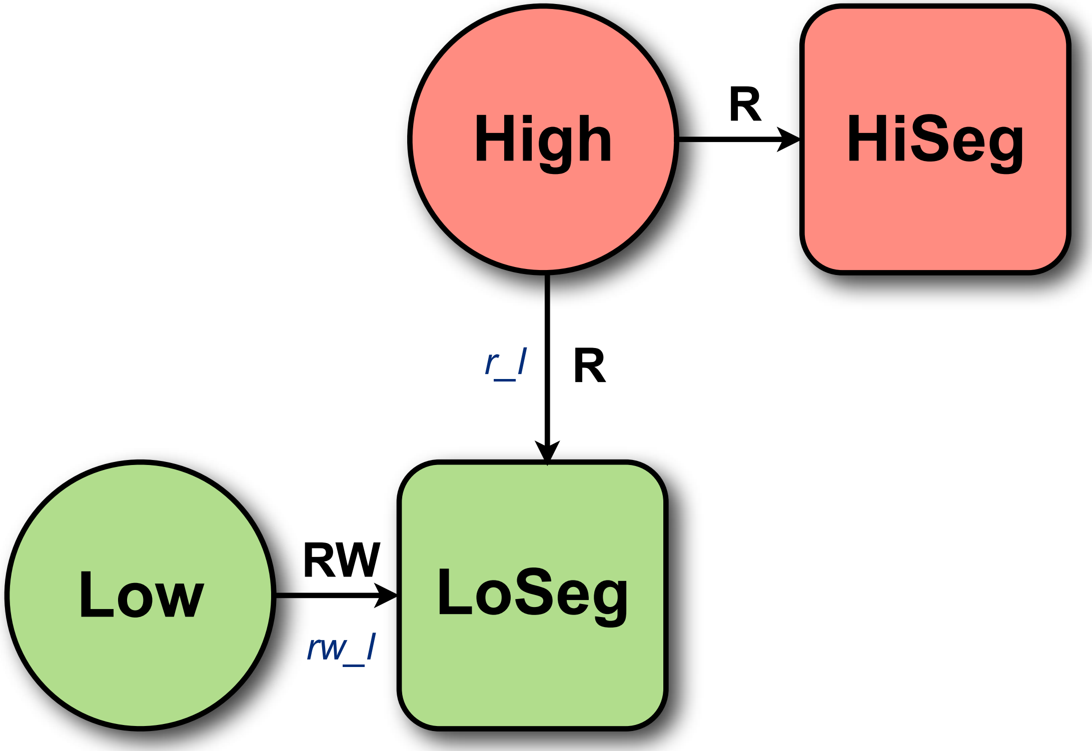
Biba Integrity Model

- Bell-LaPadula enforces **confidentiality**
- **Biba:** Its dual, enforces integrity
- Objects now carry **integrity** classification
- Subjects labelled by **lowest** level of data each subject is allowed to learn
- BLP order is inverted:
  - s can read o iff clearance(s) <= class(o)
  - s can write o iff clearance(s) >= class(o)

Boebert’s Attack

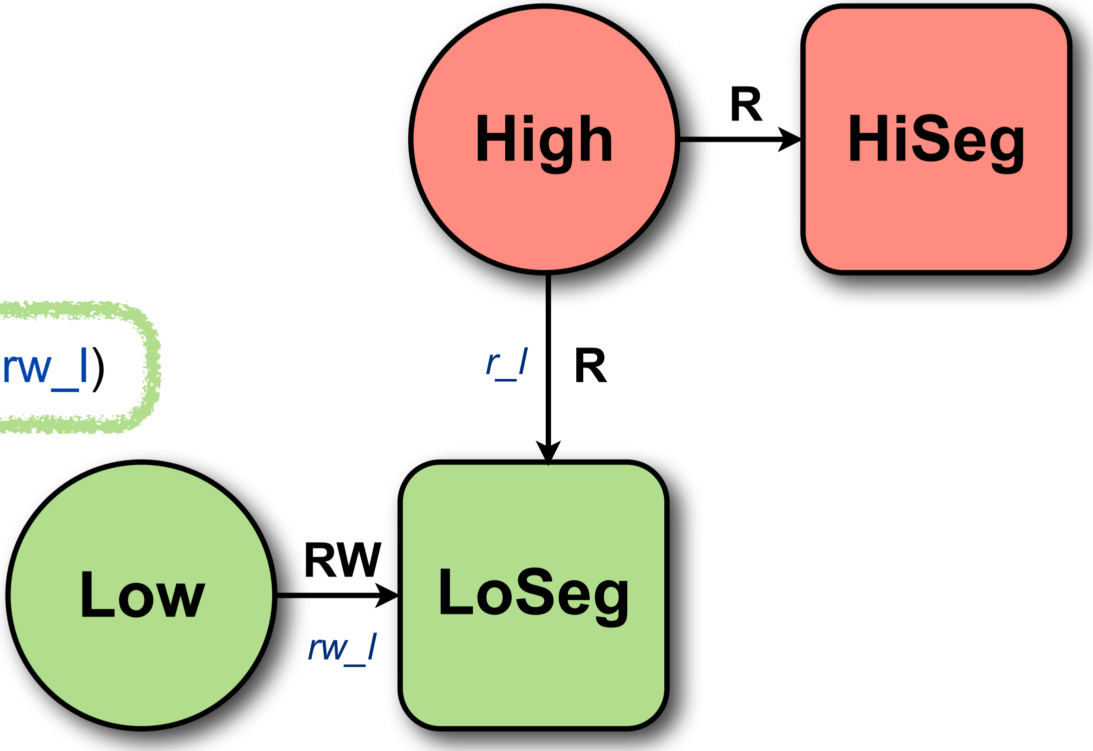
- Boebert 1984: “On the Inability of an Unmodified Capability Machine to Enforce the *-Property“
- Shows an attack on **sparse** capability systems that violates the *-property
  - Where caps and data are indistinguishable
  - Does not work against **partitioned** capability systems
    - Practically all capability-based kernels

Boebert's Attack



Boebert's Attack

rw_l.write(rw_l)



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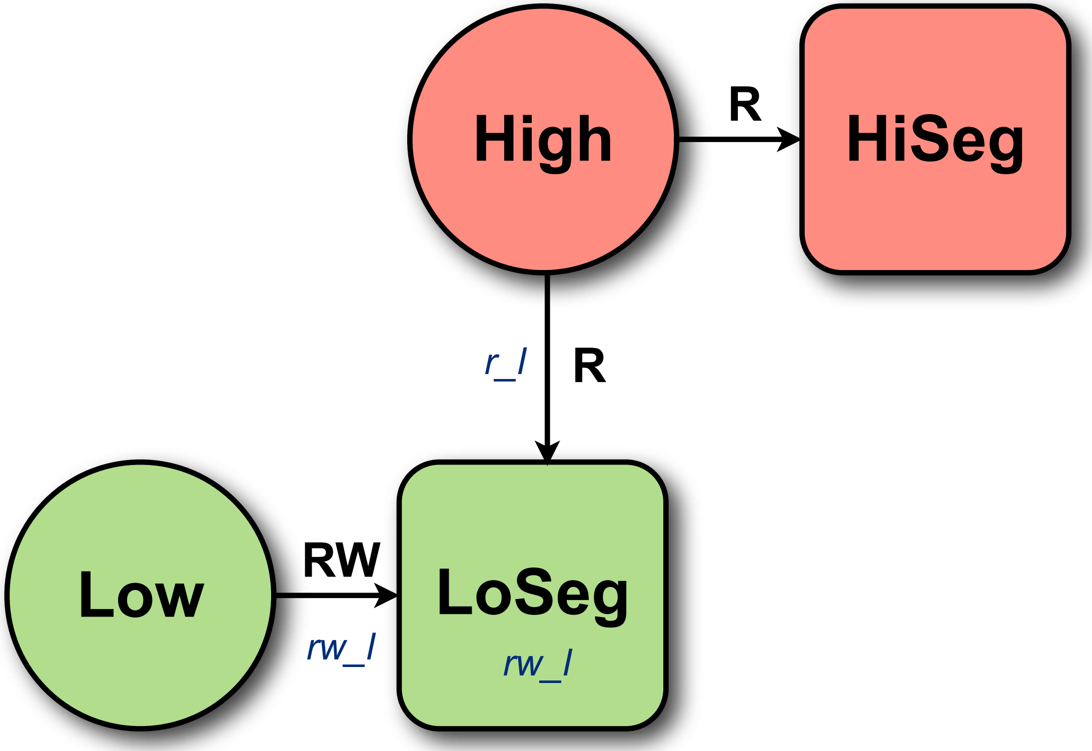
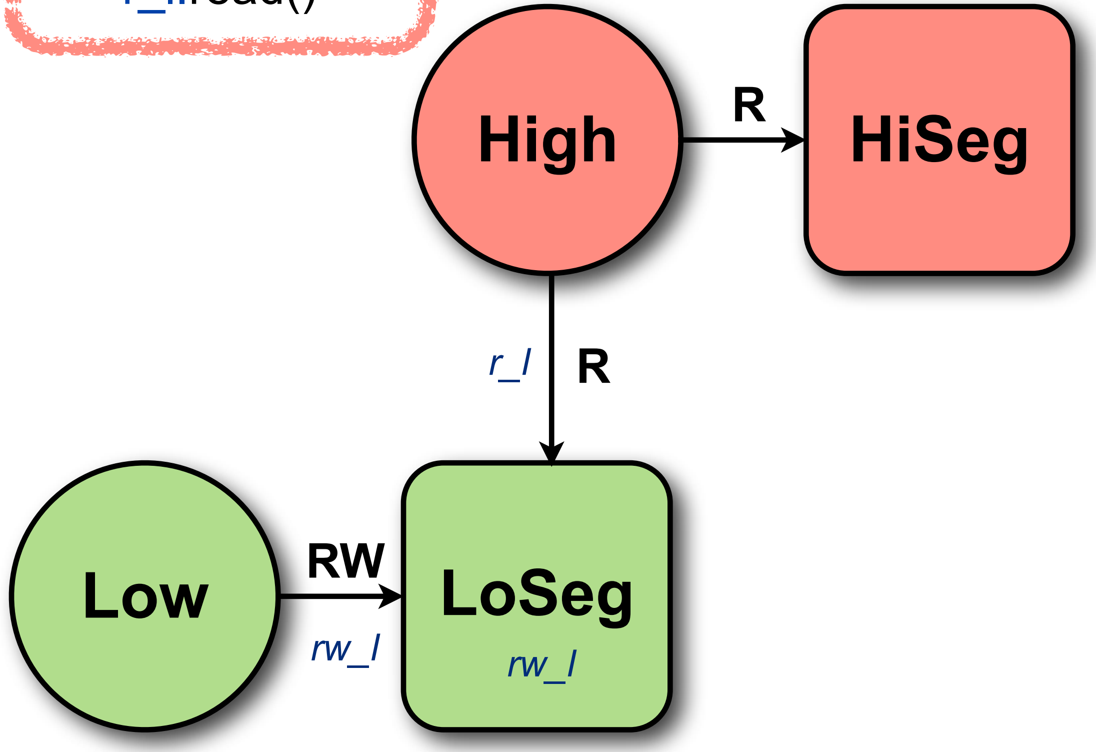


Boebert's Attack

r_l.read()



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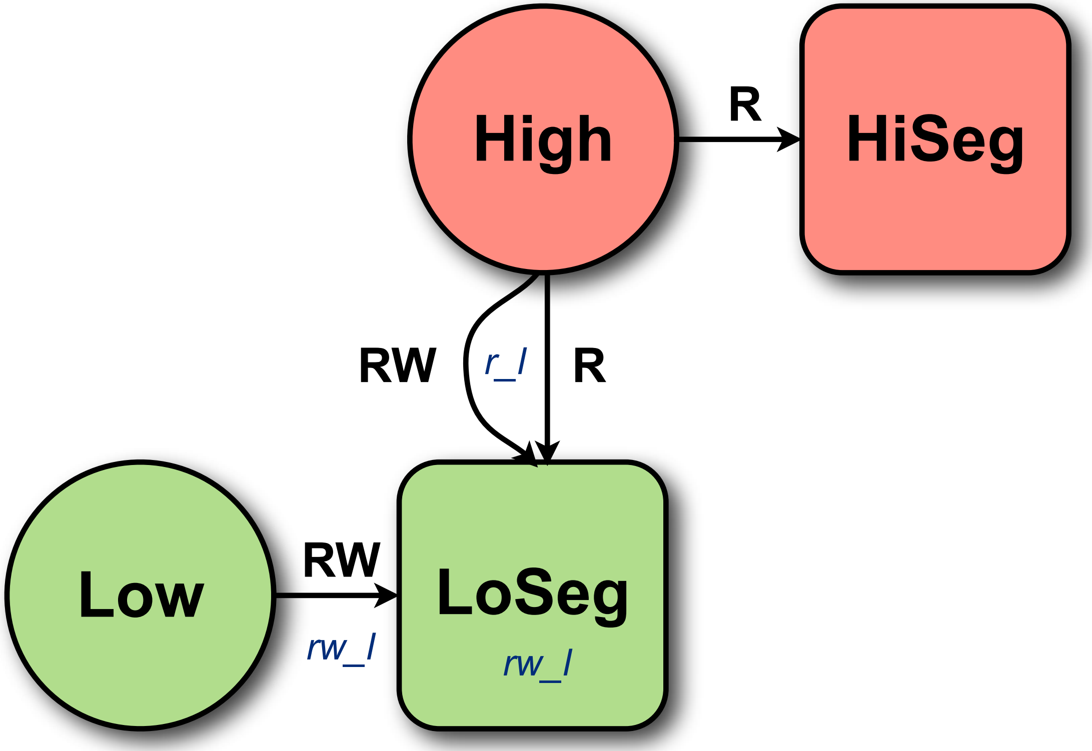

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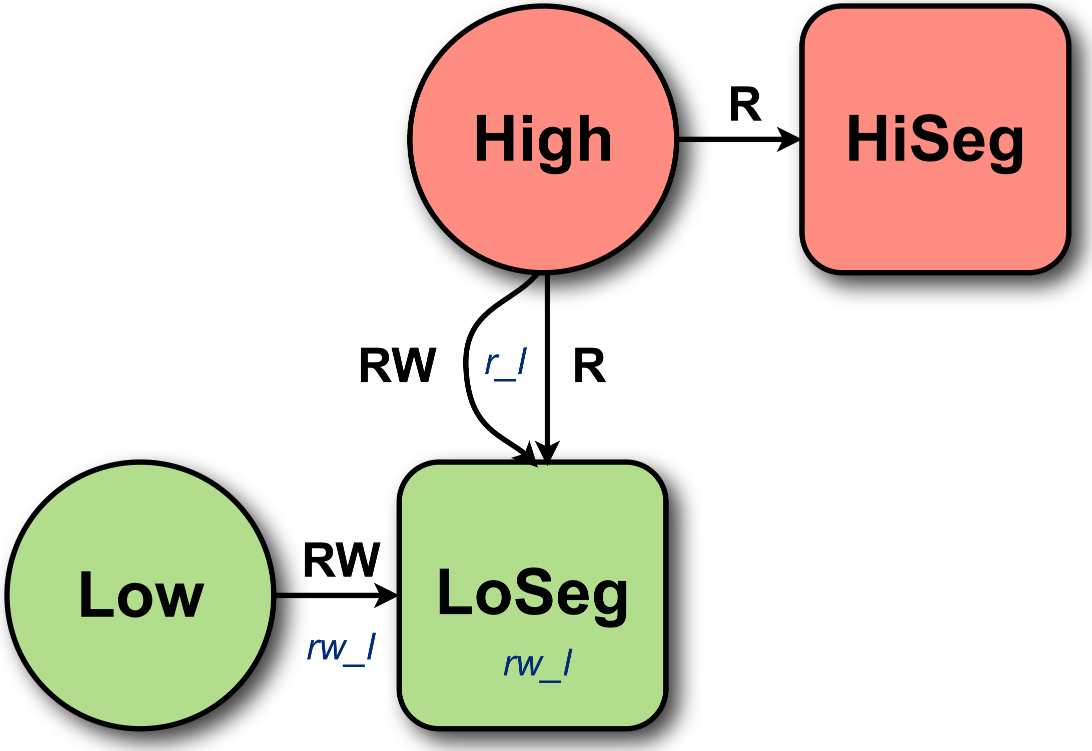


- Low writes his cap into the low segment
  - from which High reads it out

Boebert's Attack: Lessons

- Not all mechanisms suited to all policies
- Many policies treat data- and access-propagation differently
  - BLP is one example
  - Cannot be expressed using sparse capability systems
- This does **not** mean that capability systems and MAC are incompatible in general

Decideability

- Boebert’s attack highlights the need for **decideability** of safety in an AC system
- **Safety Problem:** given an initial protection state s, and a possible future protection state s’, can s’ be reached from s?
  - i.e. can an arbitrary (unwanted) access propagation occur?
- **HRU 1975:** undecideable in general
  - equivalent to the halting problem

Decideable AC systems

- The safety problem for an AC system is **decideable** if we can always answer this question mechanically
- Most capability-based AC systems decideable:
  - instances of Lipton-Snyder **Take-Grant** access control model
  - Take-Grant is decideable in linear time
- Less clear for many common ACL systems

Summary: AC Principles

- ACLs and Capabilities:
  - They are not necessarily duals in practice
  - Capabilities tend to better support least privilege
  - But ACLs can be better for auditing
- MAC good for global security requirements
- Certain kinds of policies cannot be enforced with certain kinds of mechanisms
  - e.g. *-property with sparse capabilities
- AC systems should be decideable
  - so we can reason about them

ACCESS CONTROL PRACTICE

Case Study: SELinux

- NSA-developed MAC for Linux
- Designed to protect systems from buggy applications
  - Especially daemons and servers that have traditionally run with superuser privileges
- Adds a layer of MAC atop Linux's traditional DAC
  - Each access check must pass both the normal DAC checks and the new MAC ones
- Used widely in e.g. RHEL

SELinux: Policy

- **Domain-Type Enforcement:**
  - Each process labelled with a **domain**
  - Each object labelled with a **type**
  - Central policy describes allowed accesses from domains to types
- Example:
  - `named` runs in `named_d` domain; `/sbin` labelled with `sbin_t` type
  - "`allow named_d sbin_t:dir search`"

SELinux: Domain/Type Transitions

- How domains assigned to new processes
  - upon exec() (after fork())
  - based on exec'ing domain and exec'd file type
  - "`type_transition initrc_d squid_exec_t:process squid_d`"
- how types assigned to new files/directories
  - based on domain of process creating them and type of parent directory
  - "`type_transition named_t var_run_t:sock_file named_var_run_t`"

SELinux

- Static fine-grained MAC
- Monolithic policy of high complexity
    - “The simpler targeted policy consists of more than 20,000 concatenated lines ... derived from ... thousands of lines of TE rules and file context settings, all interacting in very complex ways.”
        - – Red Hat Enterprise Linux 4: Red Hat SELinux Guide, Chapter 6. Tools for Manipulating and Analyzing SELinux
- Limited flexibility
    - – What authority should we grant a text editor?
        - Needed authority determined only by user actions

Case Study: Capsicum

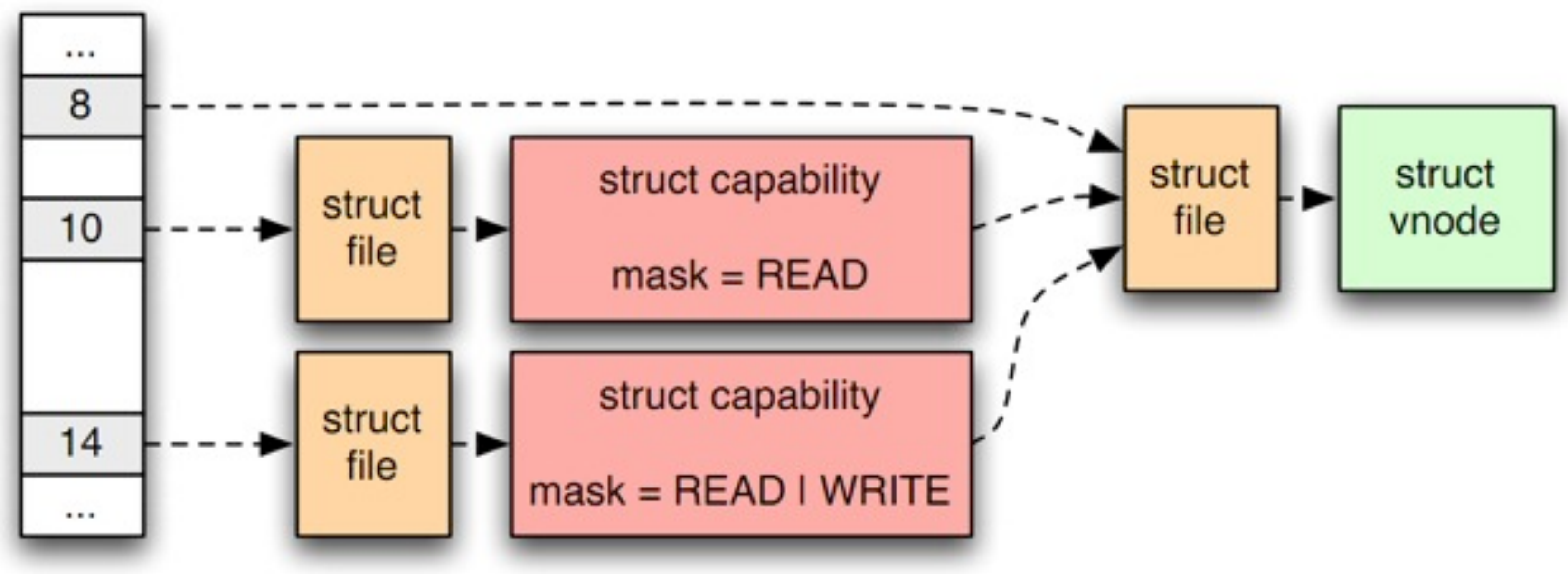
- “Practical Capabilities for UNIX” (Watson et al., USENIX Security 2010)
- Designed to support least privilege in conventional systems
  - without downsides of MAC
  - through delegation
- Merged into FreeBSD 9
  - But turned off by default

Capsicum: Kernel

- Capsicum adds to the FreeBSD kernel:
  - Capabilities with fine-grained access rights for standard objects (files, processes etc.)
  - Capability Mode
    - Disallows access to global namespaces (e.g. filesystem etc.)
    - All accesses must go through capabilities
    - *at() system calls can resolve only names “underneath” the passed descriptor
    - Allows access to subsets of the filesystem by directory capabilities

FreeBSD Capsicum: Capabilities

- New file descriptor type
  - Wrap traditional file descriptors
  - Carry fine-grained access rights



FreeBSD Capsicum: Capabilities

- Capability passing as for file descriptors:
  - may be inherited across fork()
  - passed via UNIX domain sockets
- Created using cap_new()
  - From a raw file descriptor and a set of rights
  - Or an existing capability
    - New cap's rights must be a subset
- Capabilities may refer to files, directories, processes, network sockets etc.

FreeBSD Capsicum: Capability Mode

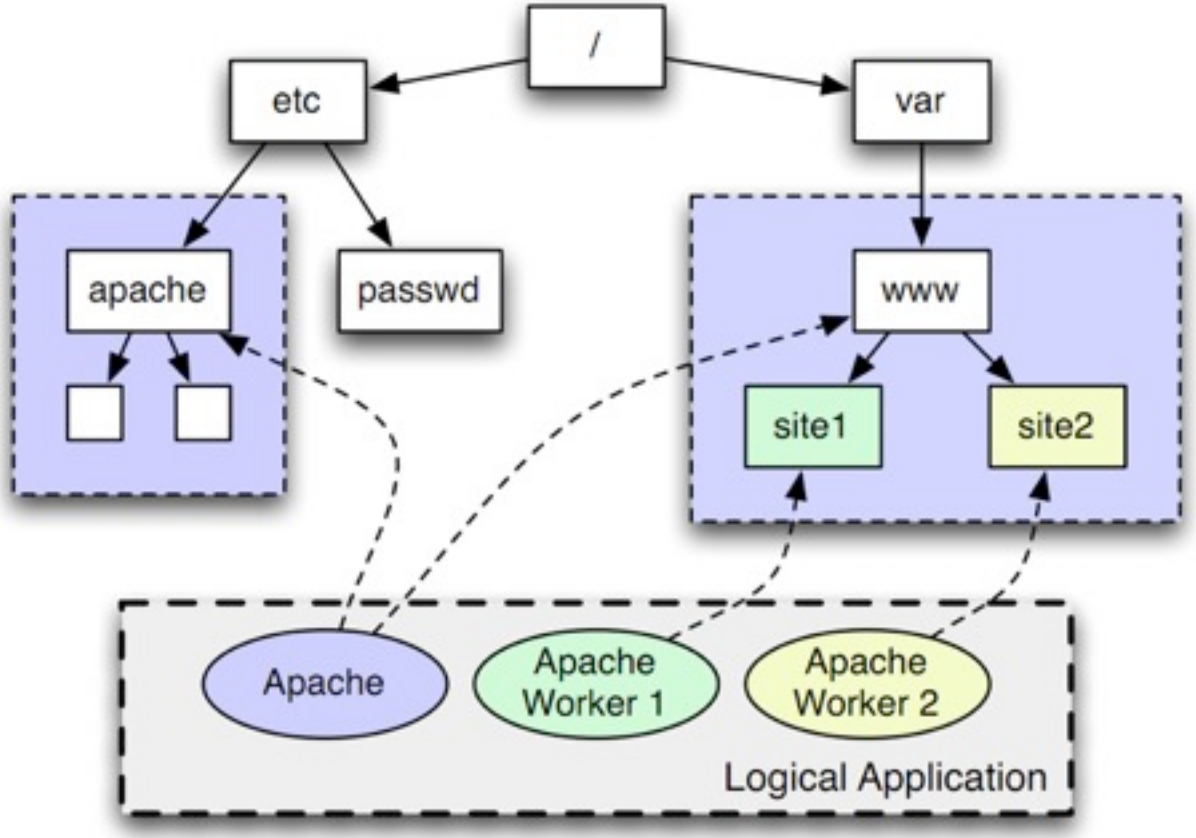
- Entered via new syscall: cap_enter()
  - Sets a flag that all child processes then inherit and can never be cleared once set
- Disallows access to all global namespaces:
  - Process ID (PID), file paths, protocol addresses (e.g. IP addrs), system clocks etc.
    - e.g. open() syscall disallowed (but openat() OK)
  - All accesses through delegated capabilities
    - Removes all ambient authority

FreeBSD Capsicum: *at() syscalls

- Allow lookups of paths relative to a given directory
  - specified by a directory file descriptor
  - e.g. `openat(rootdirfd,”somepath”, O_RDONLY)`
- In capability mode, prevented from traversing any path above the given cap
  - e.g. `openat(dirfd,”../blah”, flags)` disallowed
  - Ensures that directory caps do not confer authority to access their parents

FreeBSD Capsicum: Capability Mode

- Directory capabilities allow access to sub-parts of the filesystem namespace



FreeBSD Capsicum: Delegation

- A parent delegates to an app it invokes by:
  - fork()ing, obtaining a cap to the child
  - child drops or weakens unneeded caps, calls cap_enter(), then exec()s invoked binary
- Allows e.g. your shell to delegate sensibly to apps it invokes
  - Although apps need to be modified to do all accesses via capabilities
  - Provides an incremental path towards security

Filenames as Cap Handles

- Capsicum: `openat()` maps filenames to caps
  - relative to some root directory cap
  - filenames become capability handles
- Unestos (Krohn et al., HotOS 2005)
  - no global namespaces, ever
    - each process has distinct filesystem namespace, like in Plan 9
  - all resources represented in filesystem
    - e.g. /sockets/tcp/listen/80
  - all filenames are just string handles for caps
    - file namespace becomes simply a cap namespace

AC Mechanisms and Least Privilege

- Secure OS should support writing least-privilege applications
  - – decomposing app into distinct components
  - – each of which runs with least privilege
- Largely comes down to its AC system
  - – some make this far more easy than others
- Example: web browser
  - – handles lots of the user's sensitive info
  - – but processes lots of untrusted input
  - – input processing parts need to be sandboxed

Sandboxing Chromium (Watson et al., 2010)

	OS	Sandbox	LOC	FS	IPC	Net	Priv
DAC	Windows	DAC ACLs	22,350	⚠	⚠	✗	✓
	Linux	chroot()	600	✓	✗	✗	✗
MAC	OS X	Sandbox	560	✓	⚠	✓	✓
	Linux	SELinux	200	✓	⚠	✓	✗
Caps	Linux	seccomp	11,300	⚠	✓	✓	✓
	FreeBSD	Capsicum	100	✓	✓	✓	✓

USABLE SECURITY

Users and Security

- “The single biggest cause of network security breaches is not software bugs and unknown network vulnerabilities but user stupidity, according to a survey published by computer consultancy firm @Stake.”
  - http://www.zdnetasia.com/staff-oblivious-to-computer-security-threats-21201228.htm
- “if [educating users] was going to work, it would have worked by now.”
  - http://www.ranum.com/security/computer_security/editorials/dumb/

Security Advice

- Security advice:
  - e.g. check URLs / HTTPS certs, use strong passwords, don’t write down passwords, etc.
- Is regularly rejected:
  - when it makes it impossible to get work done
    - why bosses share their passwords with their PAs
  - when there is some incentive to do so
    - why users give out their passwords for chocolate
  - when nobody ever sees any threat
    - why nobody checks HTTPS certificates
    - who here has ever faced a live MITM?

Security Advice Rejection

- Is often rational (Herley, NSPW 2009)
  - because it costs more to follow it than not to
    - advice imposes a cost on **everyone**
    - but only a **fraction** ever get attacked
    - so for most, there is not benefit
- Is because security is secondary concern
  - people get paid (only) for getting work done
- Writing good security advice is **hard**
  - this says more about poor system design than about the motivations of end-users

A brief digression...

- Has your bank ever reminded you not to forget your ATM card when withdrawing cash?

User Education

- Needed when the most secure way to use a system differs from the easiest
  - for rational users: “easiest” = “most profitable”
    - will be different for different people
- Is expensive
  - Cheaper to avoid need for it by careful design
- Not always possible to avoid:
  - when security and productivity goals conflict
  - e.g. need-to-know versus intelligence sharing post 9/11

Why Usable Security?

- Design Principle: Make the easiest way to use a system the most secure
  - c.f. safe defaults
- In general: exploit the user to make the system more, not less, secure
  - by aligning their incentives to produce behaviour that enhances security
  - requires good understanding of economics, human behaviour, psychology etc.
    - why these are now becoming hot topics in security research

Secure Interaction Design

- Users often behave “insecurely” because their actions cause effects different to what they expect
  - User types password into a phishing website
    - did not expect the website was fraudulent
  - User executes email attachment
    - did not expect the attachment to be dangerous
- General principle: secure systems must behave in accordance with user expectations

User Expectations

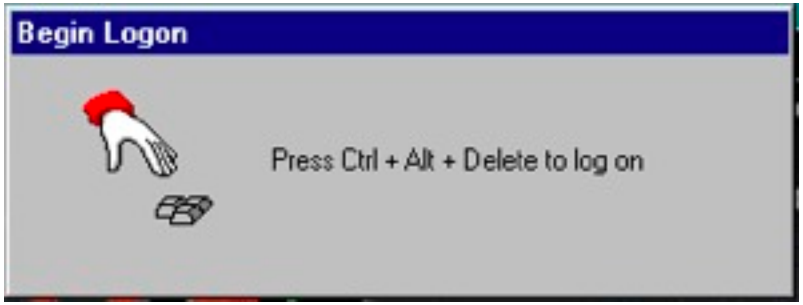
- To behave in accordance with user expectations:
  - Software must clearly convey consequences of any security choices presented to user
  - Software must clearly inform the user to keep accurate their mental model that informs their choices
- Why secure UIs require **trusted paths**
  - Essential security mechanism of a secure OS

Trusted Path

- Unspoofable I/O with the user
  - unspoofable output
    - so the user can believe what they see
  - unspoofable input
    - so the user knows what they say will be honoured
- Requires trustworthy I/O hardware
- For interactions via the OS, requires:
  - trustworthy drivers
  - trustworthy kernel

Secure Attention Key

- A trusted path for logging in
  - – Ctrl-Alt-Del in Windows NT-based systems
  - – Untrappable by applications, so unspoofable
  - – Traps directly to kernel
  - – Causes login prompt only to be displayed
- Requires user effort
  - – So not optimal
  - – But better than nothing



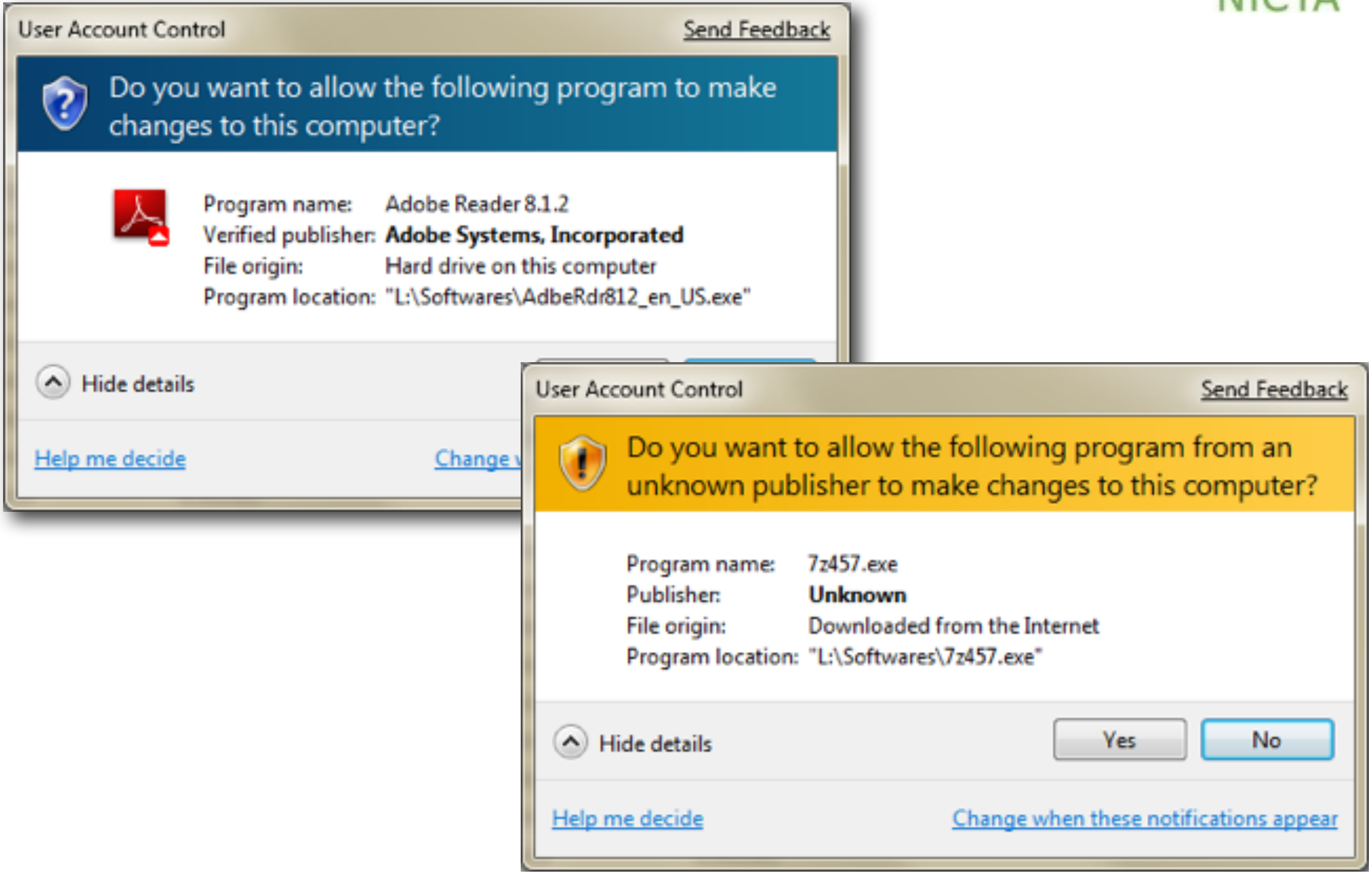
Begin Logon

Press Ctrl + Alt + Delete to log on

Hardware Trusted Paths

- For high-security situations, often cannot trust kernel or device derivers
- These use hardware-only trusted paths
  - Simple I/O hardware directly connected to security-critical device functions
    - e.g. pushbuttons (input) and LEDs (output)
  - bypasses OS
    - requires only that the hardware is trusted

Case Study: Windows UAC



User Account Control

Do you want to allow the following program to make changes to this computer?

Program name: Adobe Reader 8.1.2
Verified publisher: **Adobe Systems, Incorporated**
File origin: Hard drive on this computer
Program location: "L:\Softwares\AdbeRdr812_en_US.exe"

User Account Control

Do you want to allow the following program from an unknown publisher to make changes to this computer?

Program name: 7z457.exe
Publisher: **Unknown**
File origin: Downloaded from the Internet
Program location: "L:\Softwares\7z457.exe"

Windows UAC: Overview

- User prompted to confirm granting admin privileges to applications
  - – distinguishes apps from “known” and unknown publishers
  - – graphical trusted path used by default
    - via separate desktop session
    - prevents apps interfering with the dialog
- User offered a binary choice
  - – cannot decide ***which*** privileges to grant

UAC Levels (Windows 7 and 8)

High
- Always notify
- Don't notify when "I" make changes
  - "I" is a component of Windows (e.g. launched via Control Panel)
    - potential confused deputies
  - the default
- Don't dim desktop
  - no trusted path
- Never notify

Low

UAC as Usable Security

- On an uninfected machine:
  - User should say yes always
  - This can become the most natural action
- When the user becomes infected, then:
  - Most natural action could be the least secure
- Saying yes optimises for short-term productivity
  - So users who value short-term productivity may act insecurely

Admonition vs. Designation

- UAC is example of **security by admonition** (Yee *S&P* vol 2, no 4, 2004)
  - provide a notification
  - to which user must attend to remain secure
- Alternative is **security by designation**
  - ∫user actions simultaneously designate and authorise
    - c.f. capabilities
  - users' security decisions inferred through their usual actions

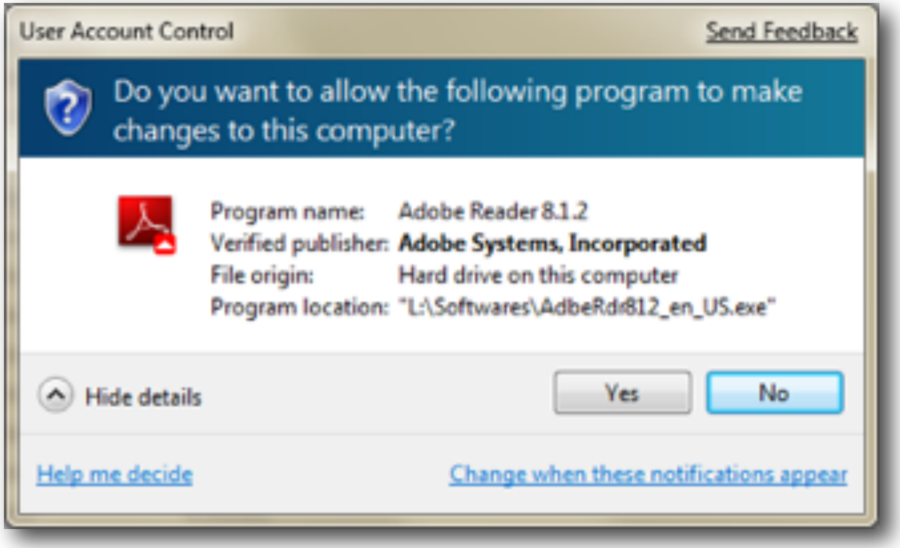
Security by Admonition

Security by Admonition

- Example: User double-clicks an app

Security by Admonition

- Example: User double-clicks an app



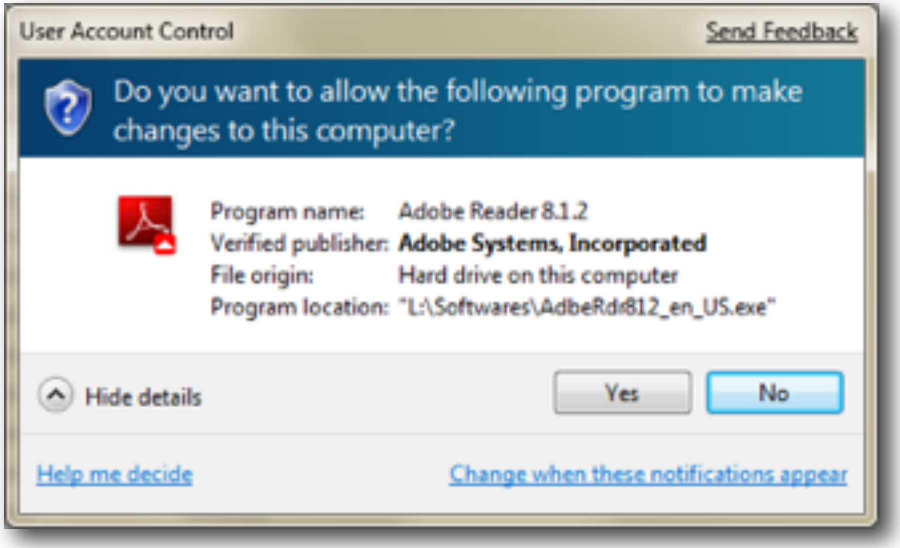
User Account Control — Send Feedback

Do you want to allow the following program to make changes to this computer?

Program name: Adobe Reader 8.1.2
Verified publisher: **Adobe Systems, Incorporated**
File origin: Hard drive on this computer
Program location: "L:\Softwares\AdbeRdr812_en_US.exe"

Security by Admonition

- Example: User double-clicks an app



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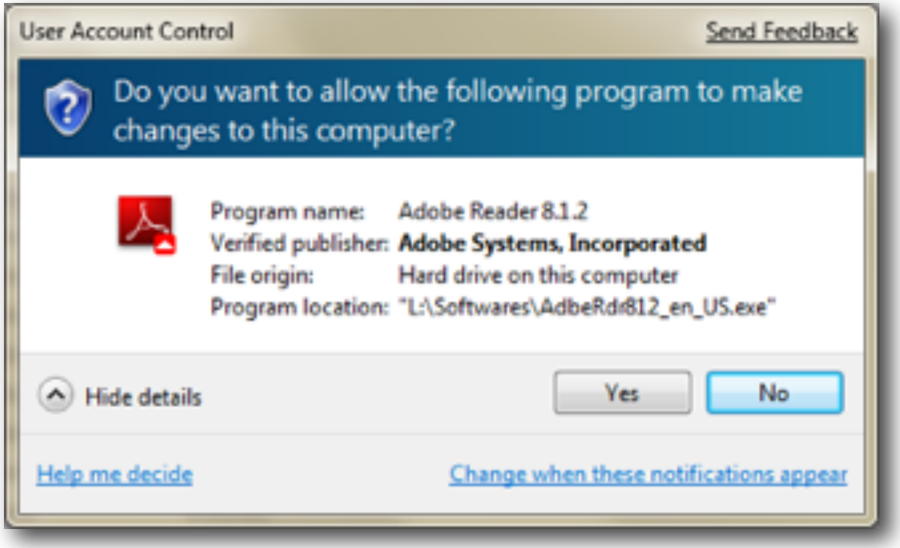
File origin: Hard drive on this computer
Program location: "L:\Softwares\AdbeRdr812_en_US.exe"

- Answer will always be "yes"
  - – unless the user clicked the wrong app

Security by Admonition

- Example: User double-clicks an app



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- Answer will always be "yes"
  - – unless the user clicked the wrong app
- "why did it 'forget' I wanted to run the app?

Security by Designation

- Example: User double-clicks an app
  - the app just runs
- User’s act of double-clicking both:
  - designates the app to run
  - grants authority for it to run
    - c.f. capabilities
- Ordinary user actions become security designations
  - ordinary actions grant appropriate authority
  - in accordance with least privilege

Case Study: OS X Lion (etc.) Powerbox

- Automatic dynamic grants of authority to **sandboxed** applications
  - inferred from ordinary user actions
- OS X sandbox:
  - an app declares its needed **authorities** via a **manifest** at install time
    - create net connection, listen, capture from camera
  - sandboxed applications' authority limited to those in its manifest
  - plus those granted to it by the user through the **powerbox damon**

OS X Lion Powerbox

- Trusted daemon process: **pboxd**
- Controls open/save dialogs (and similar)
- User selects File -> Open / Save / Save As
  - pboxd launches appropriate dialog on behalf of the app
- User selects file and clicks e.g. “Open”
  - pboxd grants the app access to the specific file / directory only
- Similar mechanism used for “Recently Opened” files etc.

OS X Lion Powerbox: MS Word

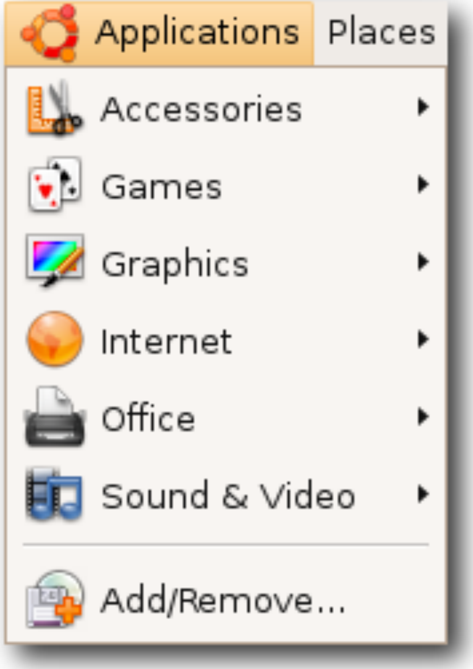
- How much authority does Word need?
  - declared statically (e.g. in its manifest):
    - ability to read/execute its shared libraries
    - ability to read/write global preferences etc.
    - i.e. access to things that were created when it was installed
  - dynamically (through the powerbox):
    - the currently opened files
- That's basically it
  - same principle can be applied to most other apps too

Least Authority Filesystem Access

- Most apps need just access to:
  - files created when the app was installed
    - /usr/lib/*appname*
  - system-wide space for app-specific data
    - /usr/share/*appname*
  - local space for user preferences
    - $HOME/*.appname*
  - files selected through the powerbox
- Basic idea behind OLPC's **Bitfrost** least-authority security architecture
  - whose creator worked on the Lion powerbox

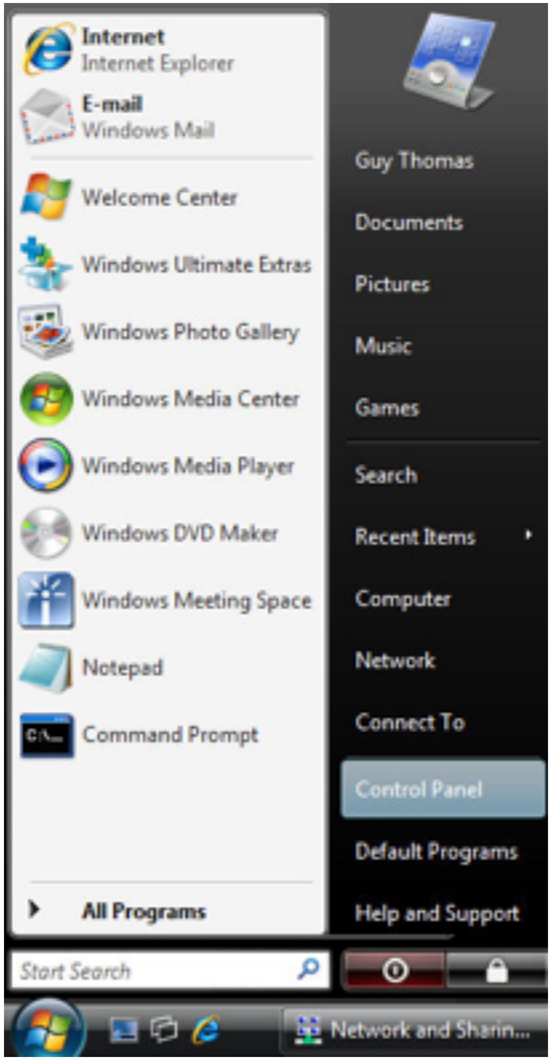
Inferring other needed authorities

- By application type (Yee 2004, IEEE *S&P*)
  - Internet
    - network access
  - Sound & Video
    - camera / mic access
  - ...
- Determined at install-time
  - user drags the app to the desired part of the applications menu
    - installs the app
    - grants it the necessary authorities



Inferring more complicated authorities

- Windows knows my default web and email clients
- Manages my passwords etc.
- Web browser has access to:
  - my bookmarks
  - web passwords, ...
- Email client has access to:
  - my mail servers
  - account names / passwords ...
- Bonus: app agnostic



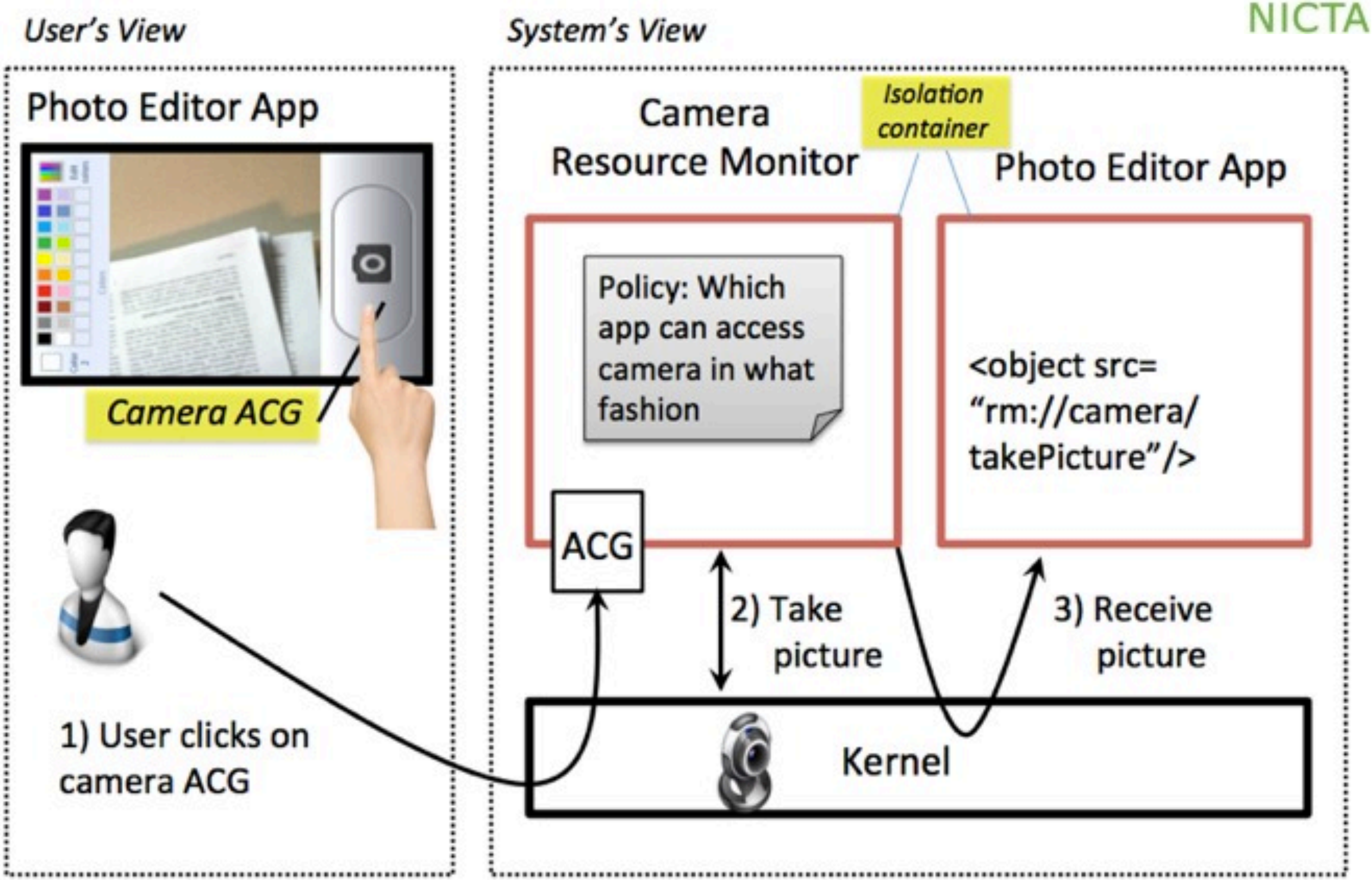
Aside: App Stores and Incentives

- Apple distributes OS X Lion apps via its App Store
- Apps need to list required authorities
- Opportunity for security:
  - allows Apple to target their application auditing processes
    - because low authority apps need less auditing
  - natural incentive for developers to minimise the authorities listed by their apps
    - low authority apps can be audited faster
- Incentives are as important as technology!

Case Study: User Driven AC (S&P 2012)

- Generalises powerbox idea from files to **arbitrary** user-owned resources
  - camera, microphone, address book, facebook friends list
- Access decisions inferred through genuine UI interactions
- Avoids user-facing manifests and UAC/ iPhone style permission popups
  - Android malware has shown that users don’t audit install-time manifests carefully
  - users tend to click-through popups

User Driven Access Control



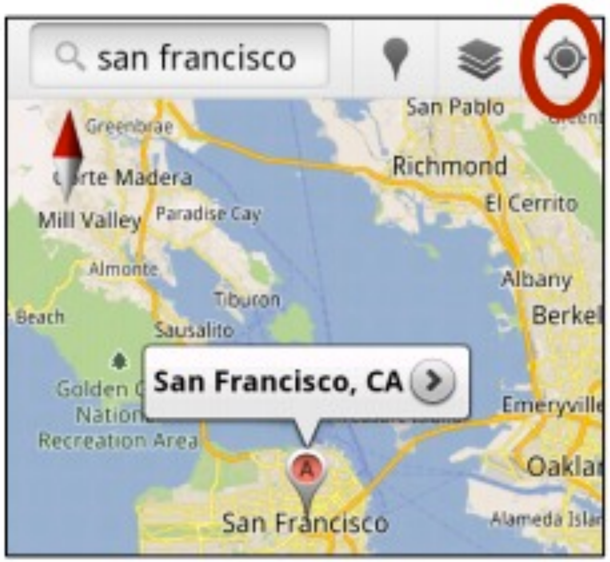
User-Driven AC

- Access Control Gadget (ACG)
  - UI element that applications can embed
  - Interacts with resource Reference Monitor
  - Interactions with ACG grant permissions to the embedding app
  - File Powerbox is but one simple ACG for files
- Protected by the OS from interference from the embedding app
  - but app can move, resize etc. embedded ACGs

ACGs and Resource Classes

ACGs and Resource Classes

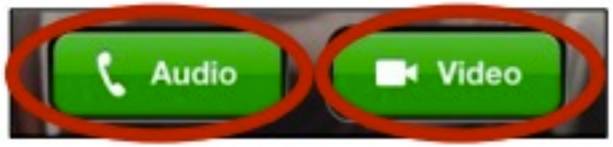
- Location data



ACGs and Resource Classes

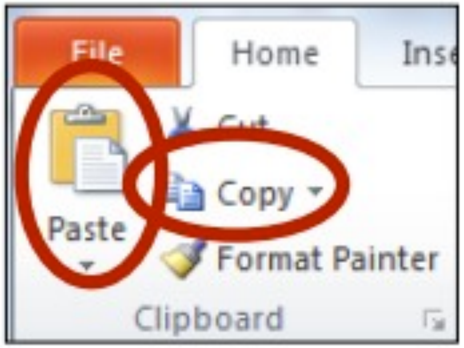
- Location data

- Microphone, camera



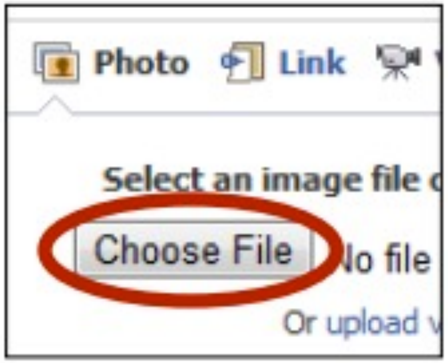
ACGs and Resource Classes

- Location data
- Microphone, camera
- Clipboard



ACGs and Resource Classes

- Location data
- Microphone, camera
- Clipboard
- Files

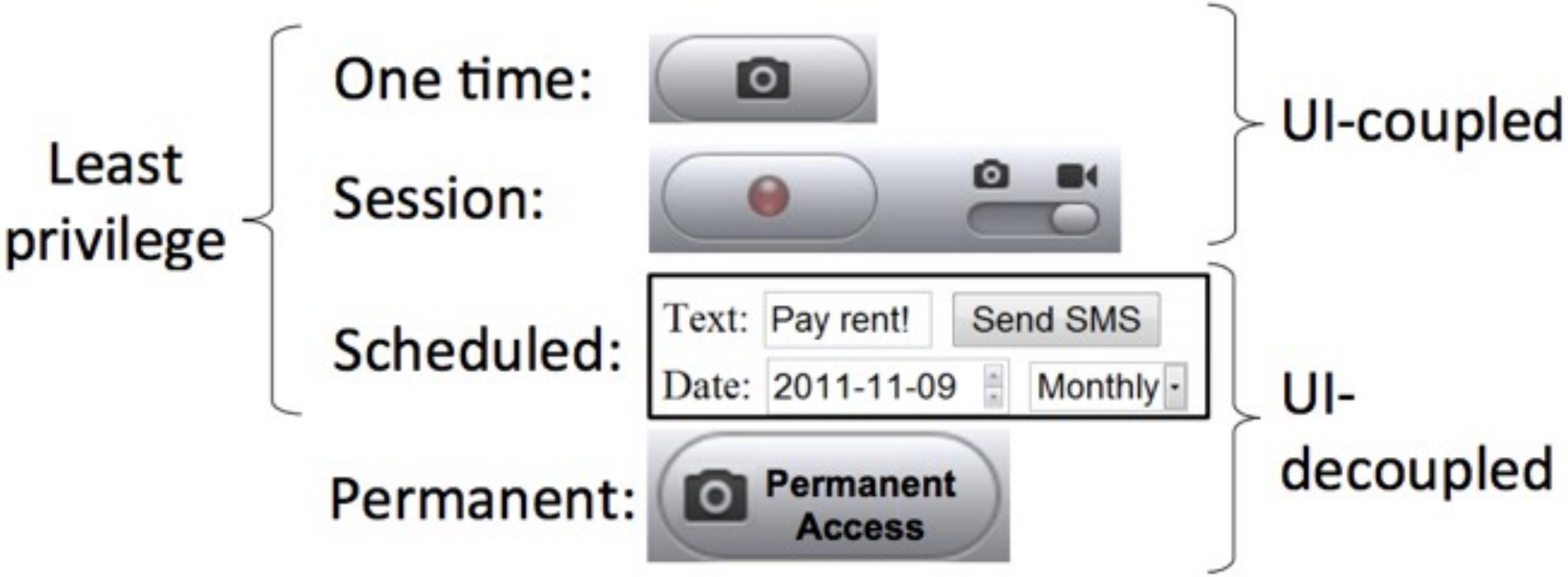


Select an image file o

Or upload v

ACGs and Access Semantics

- ACGs may grant one-time, session or permanent access
  - permanent access rarely required (5% top 100 Android apps)



Least privilege

One time:

Session:

Scheduled:

Text: Pay rent! Send SMS

Date: 2011-11-09 Monthly

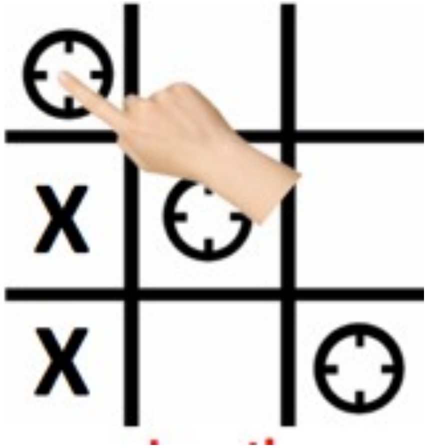
Permanent:

UI-coupled

UI-decoupled

ACGs and Trusted Path

- ACGs require a trusted path from the OS
  - – ACG input events must go directly to ACG
  - – Kernel must control the cursor over ACGs
- ACGs must be isolated from app
  - – although ACGs can allow customisation
- “Social engineering” attacks still possible
  - – trick user into granting access to current location
  - – high effort/risk for attacker



Usable Security: Summary

- Design OS security mechanisms with real users in mind
  - – mechanisms that fail when users behave normally are faulty, not the other way around
- Mechanisms must convey accurate information to users
  - – so they can make informed security decisions
- Mechanisms should infer security decisions from normal user actions
  - – granting authority according to least privilege

ASSURANCE AND VERIFICATION

Assurance: Substantiating Trust

- Specification
  - – unambiguous description of desired behaviour
- System design
  - – justification that it meets specification
    - by mathematical proof or compelling argument
- Implementation
  - – justification that it implements the design
    - by proof, code inspection, rigorous testing
- Maintenance
  - – justifies that system use meets assumptions

Common Criteria

- Common Criteria for IT Security Evaluation [ISO/IEC 15408, 99]
  - ISO standard, for general use
  - evaluates QA used to ensure systems meet their requirements
- **Target of Evaluation (TOE)** evaluated against **Security Target (ST)**
  - **ST:** statement of desired security properties based on **Protection Profiles**

Common Criteria: EALs

- 7 **Evaluated Assurance Levels**
  - **higher levels = more thorough evaluation**
    - **higher cost**
    - **not necessarily better security**

Level	Requirement	Specification	Design	Implementati
EAL1	not eval.	**Informal**	not eval.	not eval.
EAL2	not eval.	**Informal**	**Informal**	not eval.
EAL3	not eval.	**Informal**	**Informal**	not eval.
EAL4	not eval.	**Informal**	**Informal**	not eval.
EAL5	not eval.	**Semi-Formal**	**Semi-Formal**	**Informal**
EAL6	**Formal**	**Semi-Formal**	**Semi-Formal**	**Informal**
EAL7	**Formal**	**Formal**	**Formal**	**Informal**

Common Criteria Protection Profiles (PPs)

- Controlled Access PP (CAPP)
  - – standard OS security, up to EAL3
- Single Level Operating System PP
  - – superset of CAPP, up to EAL4+
- Labelled Security PP
  - – MAC for COTS OSes
- Multi-Level Operating System PP
  - – superset of CAPP, LSPP, up to EAL4+
- Separation Kernel Protection Profile
  - – strict partitioning, for EAL6-7

COTS OS Certifications

- EAL3:
  - Mac OS X
- EAL4:
  - 2003: Windows 2000
  - 2005: SuSE Enterprise Linux
  - 2006: Solaris 10 (EAL4+)
    - against CAPP (an EAL3 PP!)
  - 2007: Red Hat Linux (EAL4+)
- These OSes are still regularly broken!

EAL6 and above OS Certifications

- EAL6
  - Green Hills INTEGRITY-178B (EAL6+)
    - Separation Kernel Protection Profile (SKPP)
    - relatively simple hardware platform in TOE
  - Aiming for EAL7

SKPP on Commodity Hardware

NICTA

- SKPP:
  - OS provides only separation
- One Box One Wire (OB1) Project
  - Use INTEGRITY-178B to isolate VMs on commodity desktop hardware
  - Leverage existing INTEGRITY certification
    - by "porting" it to commodity platform
  - Conclusion (March 2010):
    - SKPP validation for commodity hardware platforms infeasible due to their complexity
    - SKPP has limited relevance for these platforms

Common Criteria Limitations

- Very expensive
  - rule of thumb: EAL6+ costs $1K/LOC
- Too much focus on development process
  - rather than the product that was delivered
- Lower EALs of little practical use for OSes
  - c.f. COTS OS EAL4 certifications
- Commercial Licensed Evaluation Facilities licenses rarely revoked
  - Leads to potential “race to the bottom” (Anderson & Fuloria, 2009)
  -

Formal Verification

- Based on mathematical model of system
- Proof:
  - Model satisfies security properties
    - Required by CC EAL5-7
  - The code implements the model
    - Not required by any CC EAL (informal argument only even for EAL7)
- Example: seL4 microkernel
  - 2009: proof that code implements model
  - 2011: proof that model enforces integrity
  - 2013: proof that model enforces confidentiality

Formal Verification Limitations

- Proofs are expensive
  - e.g. seL4 took ~30 py for ~10,000 LOC
- Proofs rest on assumptions
  - assume correct everything you don't model
    - e.g. compiler, details of hardware platform, etc.
  - difficult to assume that e.g. modern x86 platform is bug free!
  - full proofs best suited for systems that run on simple hardware platform
    - e.g. embedded systems
    - otherwise they're not yet worth the high cost

Automatic Analyses

- Algorithms that analyse code to detect certain kinds of defects
- Cannot generally “prove” code is correct
- But much cheaper than proofs
- Tradeoff between completeness and cost
- Need to choose the right tool for the job:
  - Testing
  - Automatic Analyses
  - Formal Proof
- Best strategy is to mix them appropriately

SEL4 AND SECURITY ASSURANCE

A 30-Year Dream

Operating Systems

R. Stockton Gaines Editor

Specification and Verification of the UCLA Unix† Security Kernel

Bruce J. Walker, Richard A. Kemmerer, and Gerald J. Popek
University of California, Los Angeles

Data Secure Unix, a kernel structured operating system, was constructed as part of an ongoing effort at UCLA to develop procedures by which operating systems can be produced and shown secure. Program verification methods were extensively applied as a constructive means of demonstrating security enforcement.

Here we report the specification and verification experience in producing a secure operating system. The work represents a significant attempt to verify a large-scale, production level software system, including all aspects from initial specification to verification of implemented code.

Key Words and Phrases: verification, security, operating systems, protection, programming methodology, ALPHARD, formal specifications, Unix, security kernel

CR Categories: 4.29, 4.35, 6.35

1. Introduction

Early attempts to make operating systems secure merely found and fixed flaws in existing systems. As these efforts failed, it became clear that piecemeal alterations were unlikely ever to succeed [20]. A more systematic method was required, presumably one that controlled the system's design and implementation. Then secure operation could be demonstrated in a stronger sense than an ingenuous claim that the last bug had been eliminated, particularly since production systems are rarely static, and errors easily introduced.

Our research seeks to develop means by which an operating system can be shown data secure, meaning that direct access to data must be possible only if the recorded protection policy permits it. The two major components of this task are: (1) developing system architectures that minimize the amount and complexity of software involved in both protection decisions and enforcement, by isolating them into *kernel* modules; and (2) applying extensive verification methods to that kernel software in order to prove that our of data security criterion is met. This paper reports on the latter part, the verification experience. Those interested in architectural issues should see [23]. Related work includes the PSOS operating system project at SRI [25] which uses the hierarchical design methodology described by Robinson and Levitt in [26], and efforts to prove communications software at the University of Texas [31].

Every verification step, from the development of top-level specifications to machine-aided proof of the Pascal code, was carried out. Although these steps were not completed for all portions of the kernel, most of the job was done for much of the kernel. The remainder is clearly more of the same. We therefore consider the project essentially complete. In this paper, as each verification step is discussed, an estimate of the completed portion of that step is given, together with an indication of the amount of work required for completion. One should realize that it is essential to carry the verification process through the steps of actual code-level proofs because most security flaws in real systems are found at this level [20]. Security flaws were found in our system during verification, despite the fact that the implementation was written carefully and tested extensively. An example of one detected loophole is explained in §2.5.

This work is aimed at several audiences: the software engineering and program verification communities, since this case study comprises one of the largest realistic program proving efforts to date; the operating systems community because the effort has involved new operating system architectures; and the security community because the research is directed at the proof of secure operation. We assume the reader is acquainted with common operating system concepts, with general program verification methods, and with common notions of abstract types and structured software. Understanding of Alphard proof

[†] Unix is a Trademark of Bell Laboratories.

This research was supported by the Advanced Research Projects Agency of the Department of Defense under Contract MDA 903-77-C-0211. Authors' present addresses: B.J. Walker and G.J. Popek, Department of Computer Science, University of California, Los Angeles, CA 90024; R.A. Kemmerer, Computer Science Department, University of California, Santa Barbara, CA 93106.
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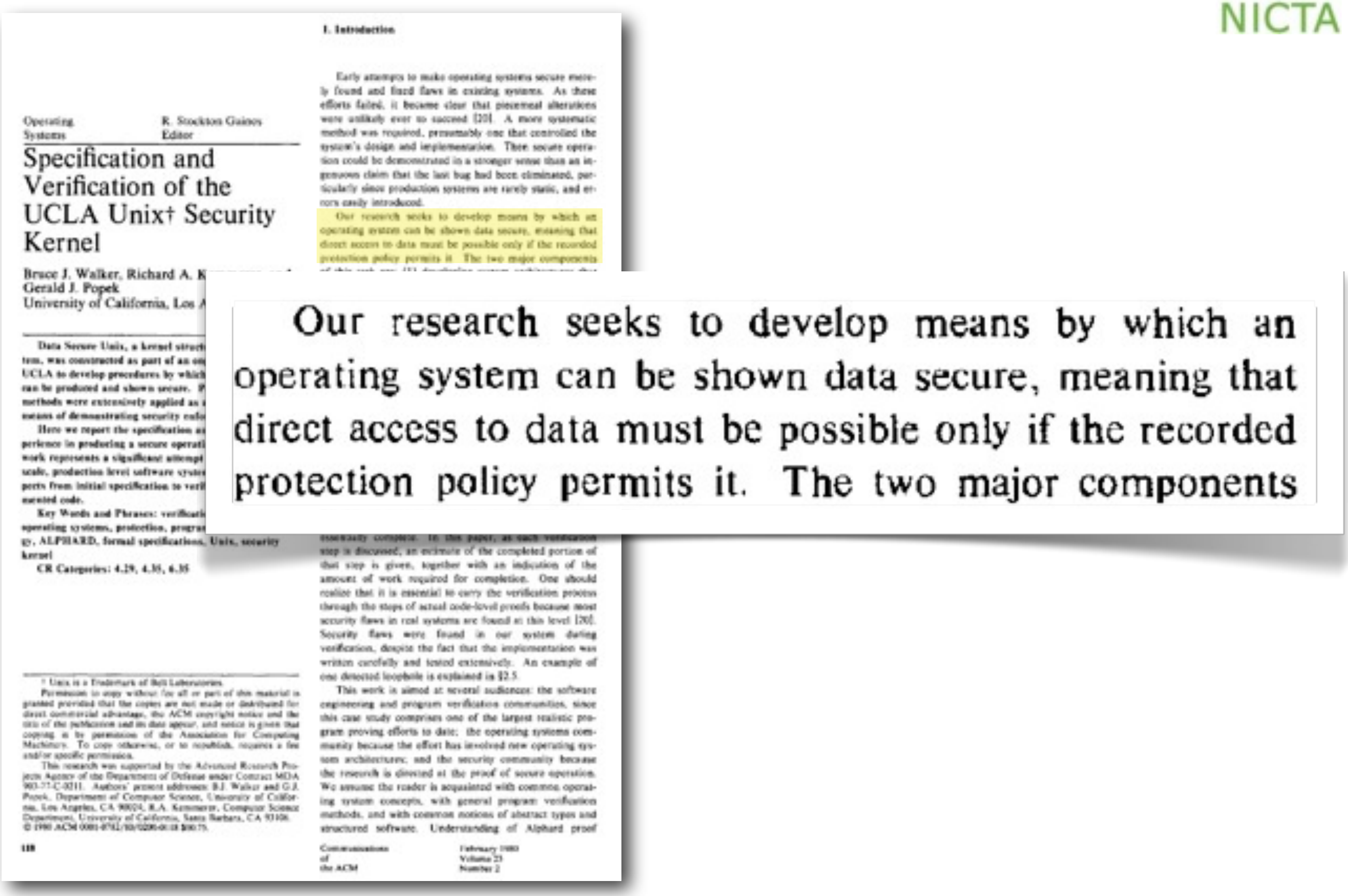

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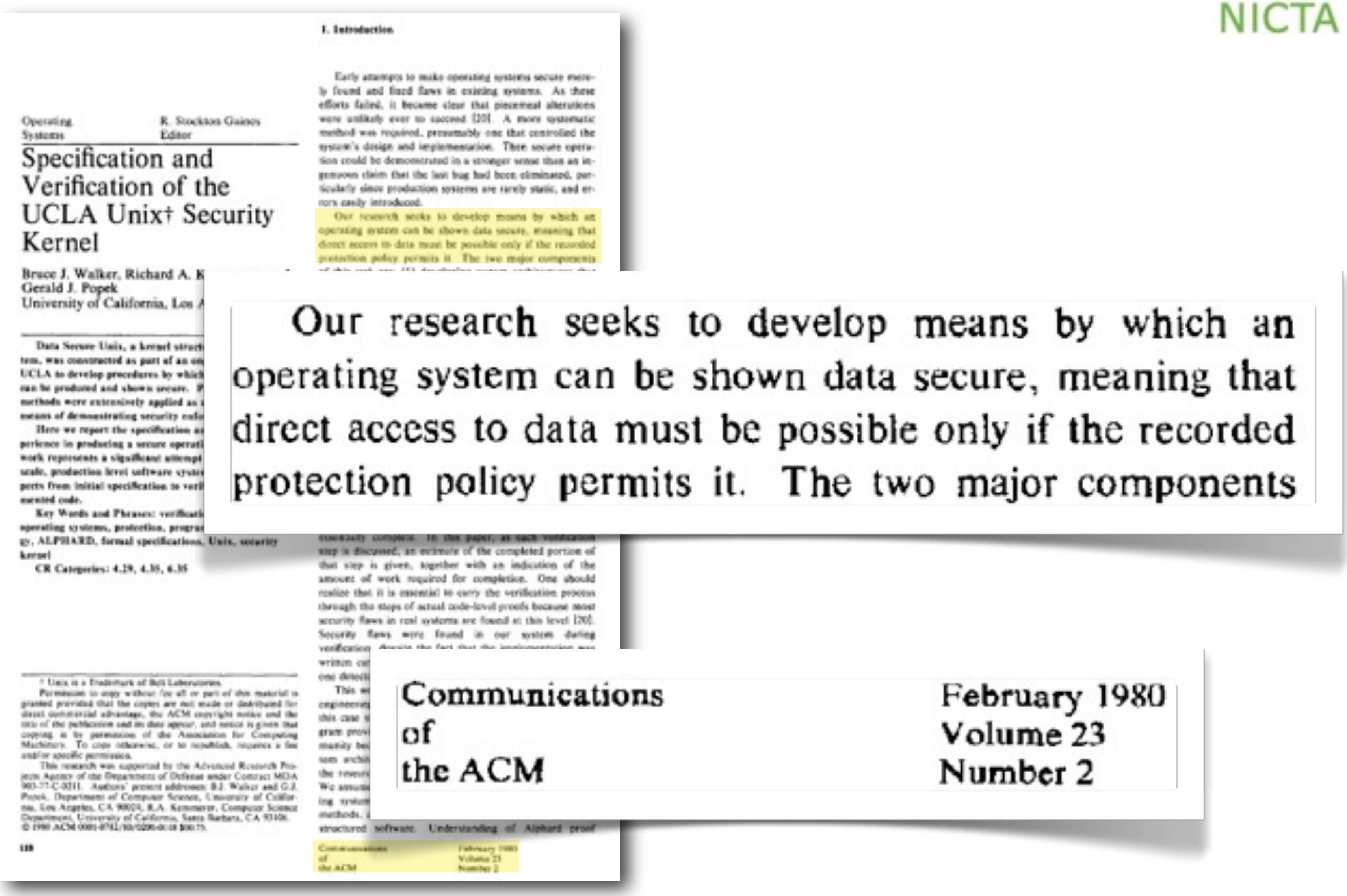

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Communications
of
the ACM

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Assurance

Common Criteria	EAL4	EAL5	EAL6	EAL7	Verified
Requirements	Informal	Formal	Formal	Formal	Formal
Functional Spec	Informal	Semiformal	Semiformal	Formal	Formal
High-Level Design	Informal	Semiformal	Semiformal	Formal	Formal
Low-Level Design	Informal	Informal	Semiformal	Semiformal	Formal
Code	Informal	Informal	Informal	Informal	Formal

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seL4

Assurance

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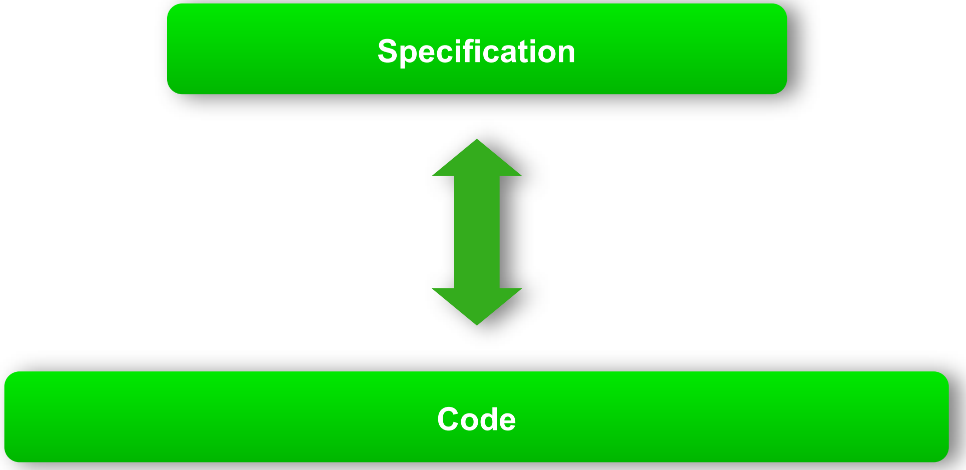
Low-Leve Design	nformal	Informal	Semiformal	Semiformal	Formal
Code	Informal	Informal	Informal	Informal	Formal

security proofs of the kernel's code

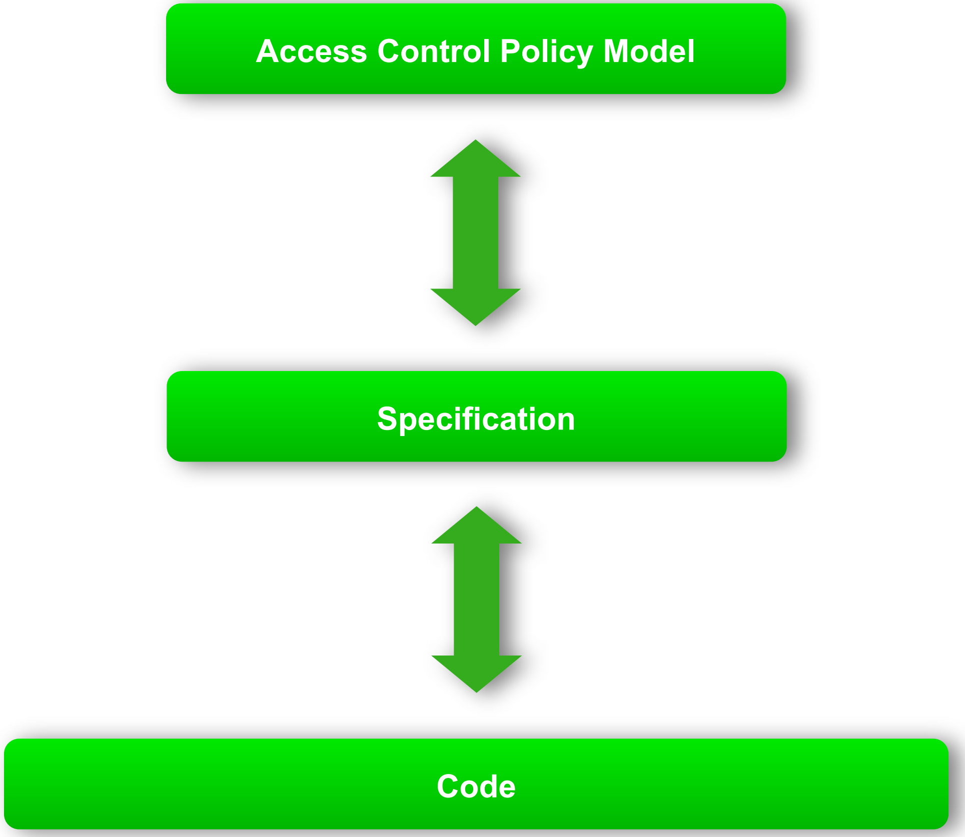
seL4 Security Proofs: Overview



Specification

Code

seL4 Security Proofs: Overview



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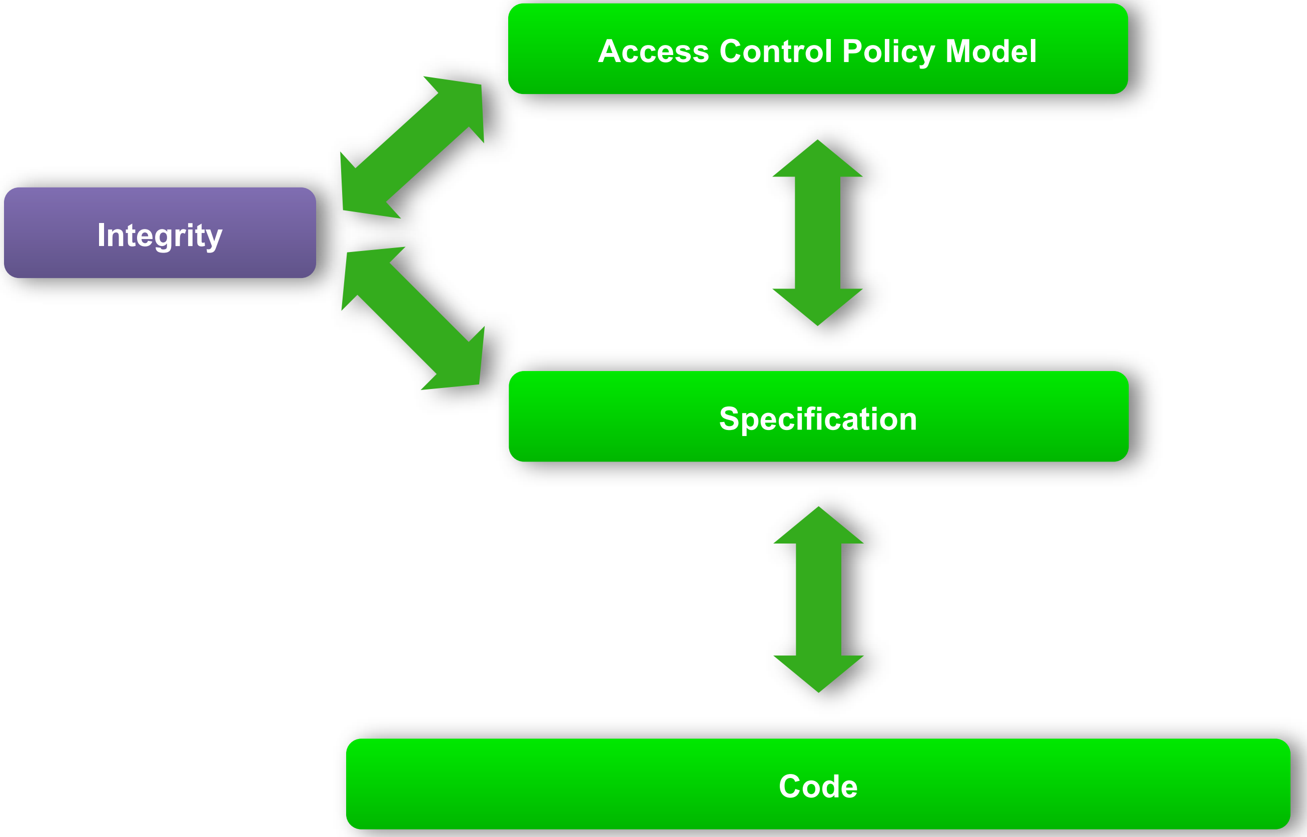

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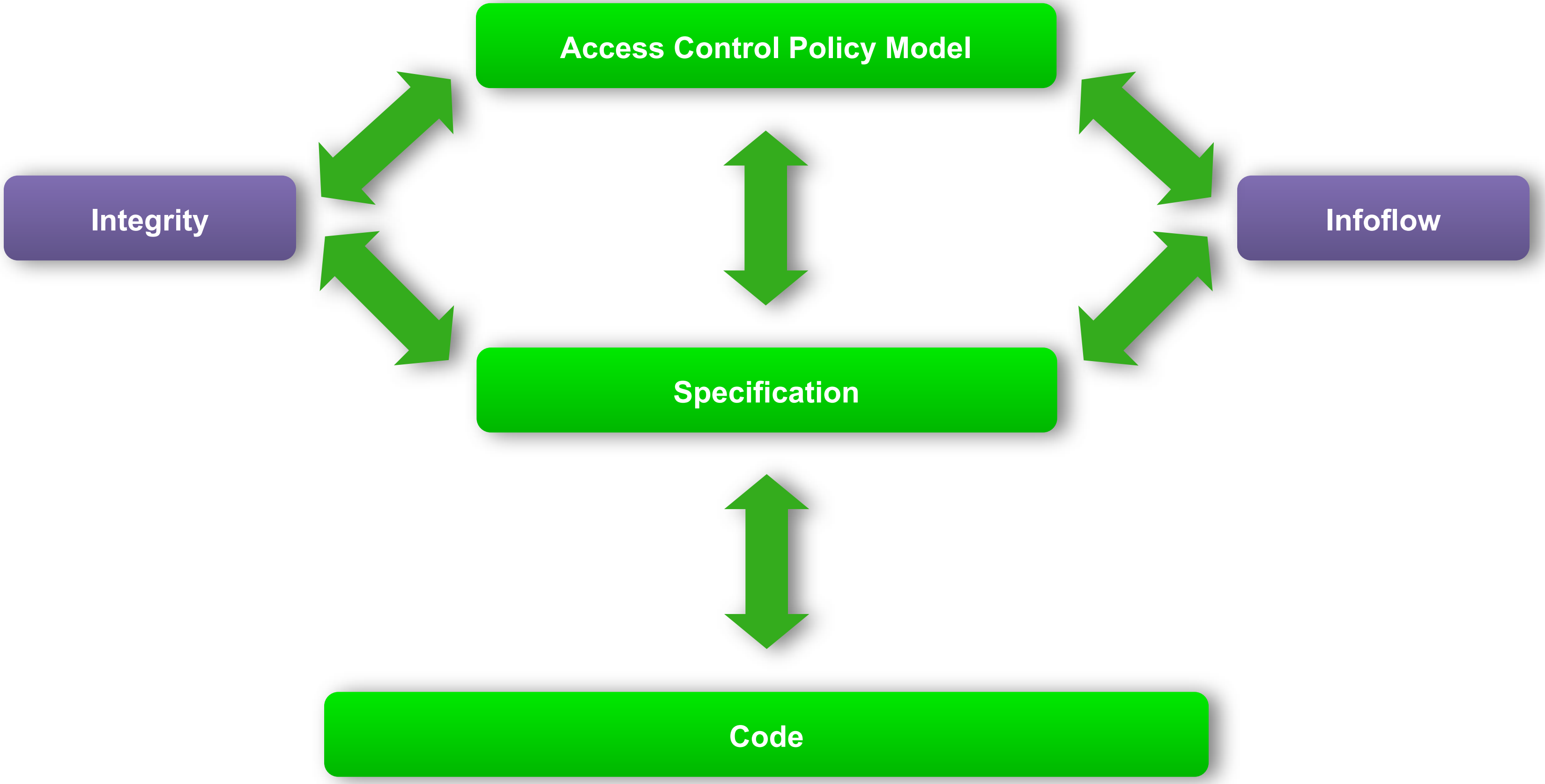
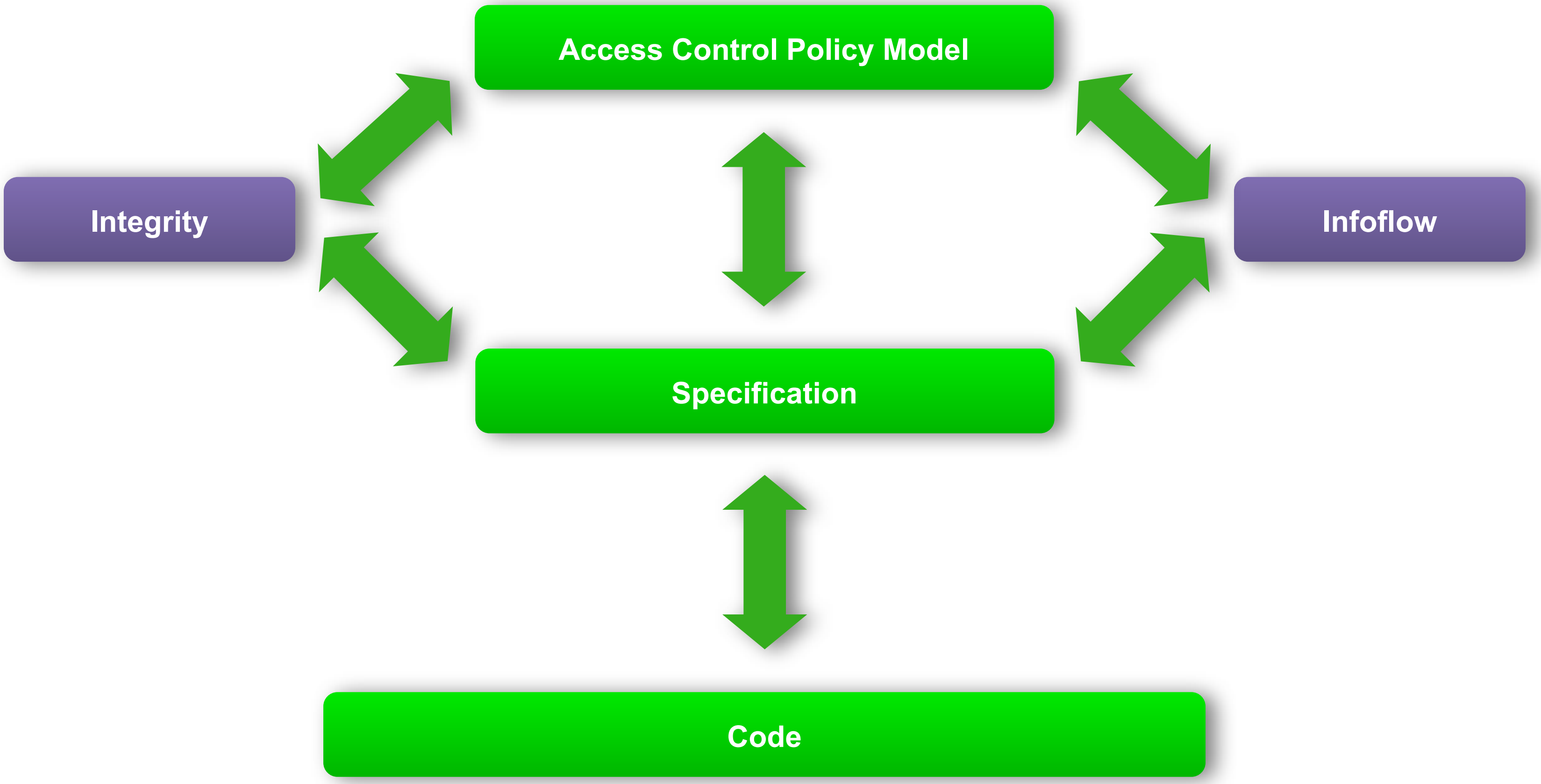


seL4 Security Proofs: Overview

Integrity + Infoflow --» Isolation



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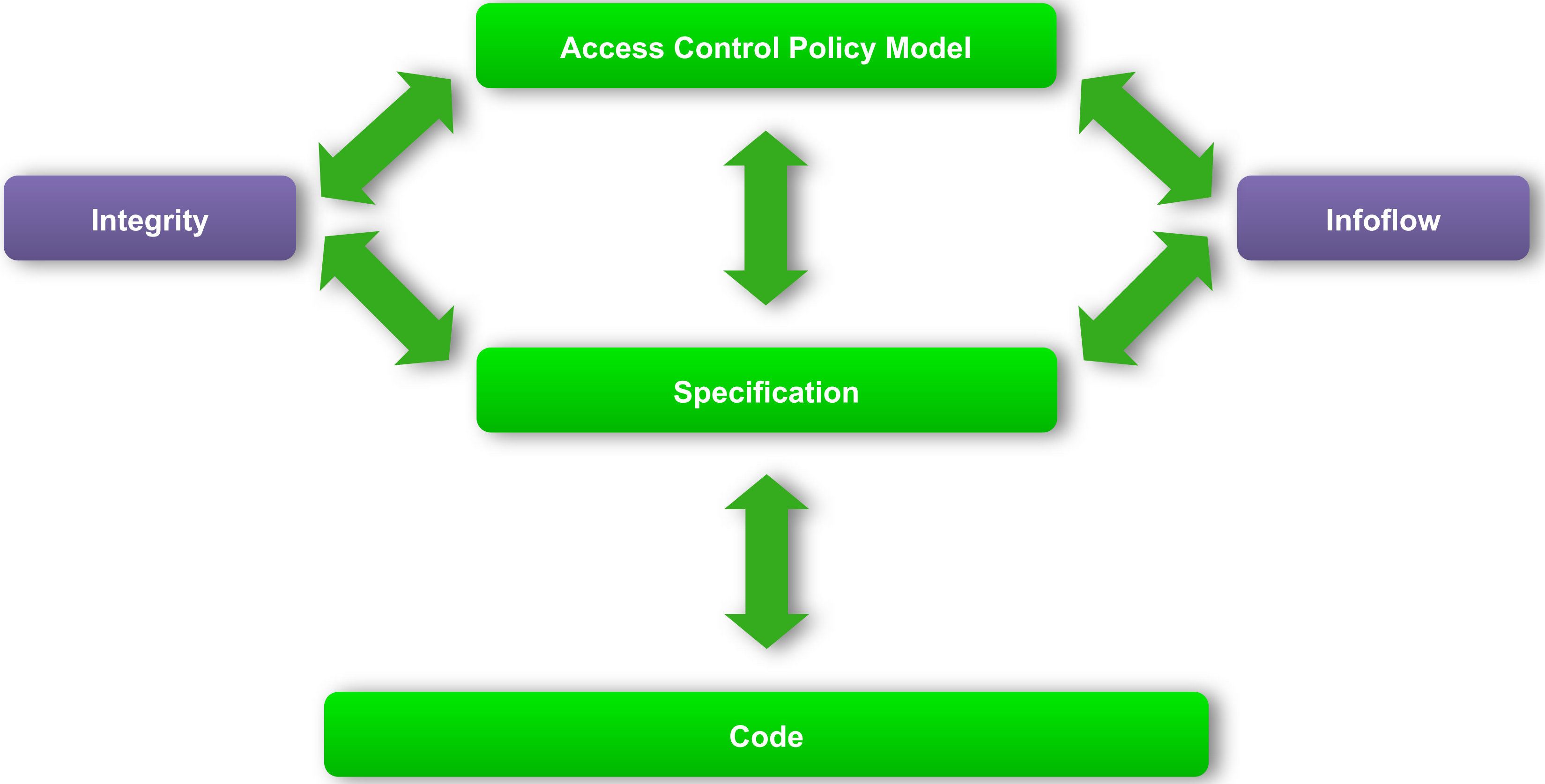

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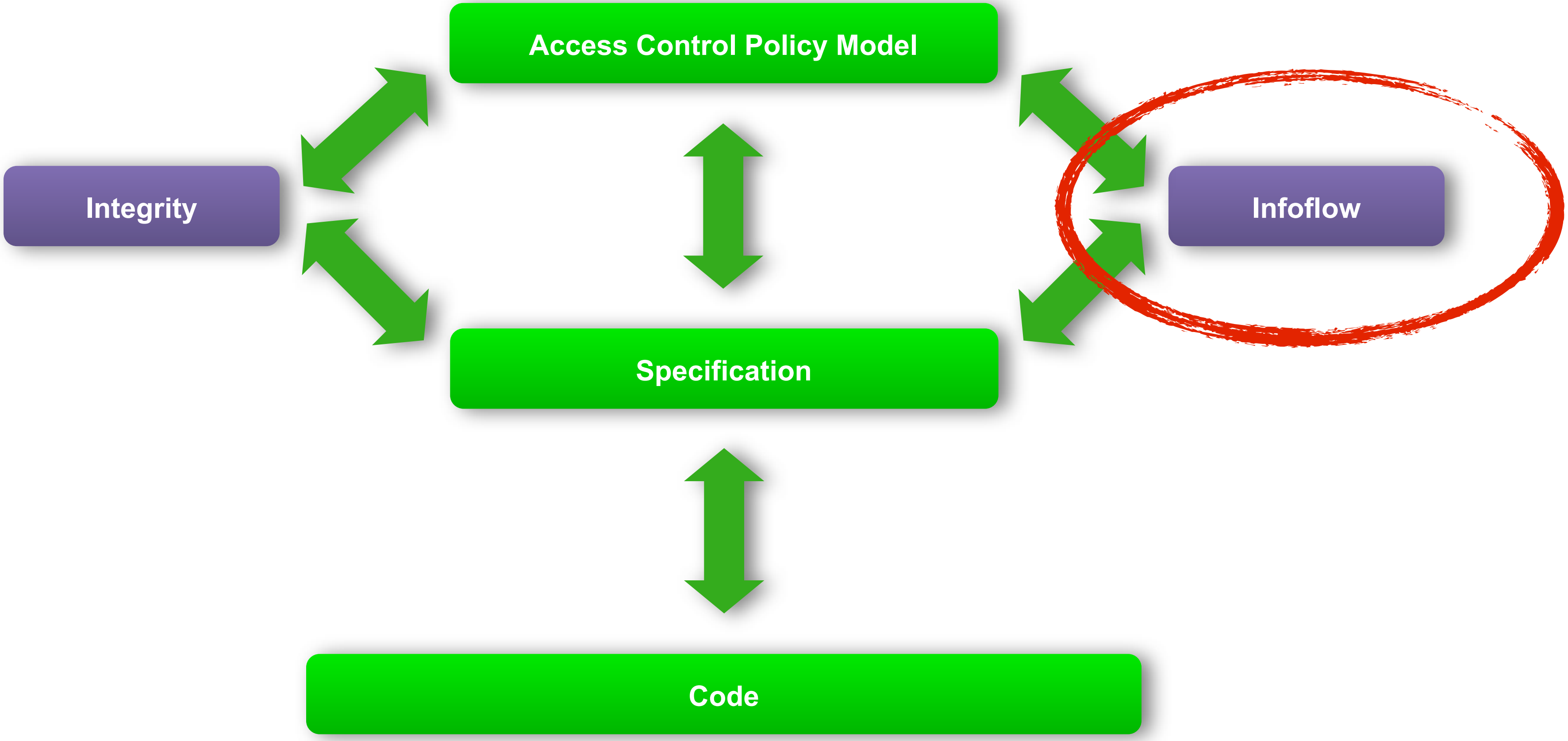

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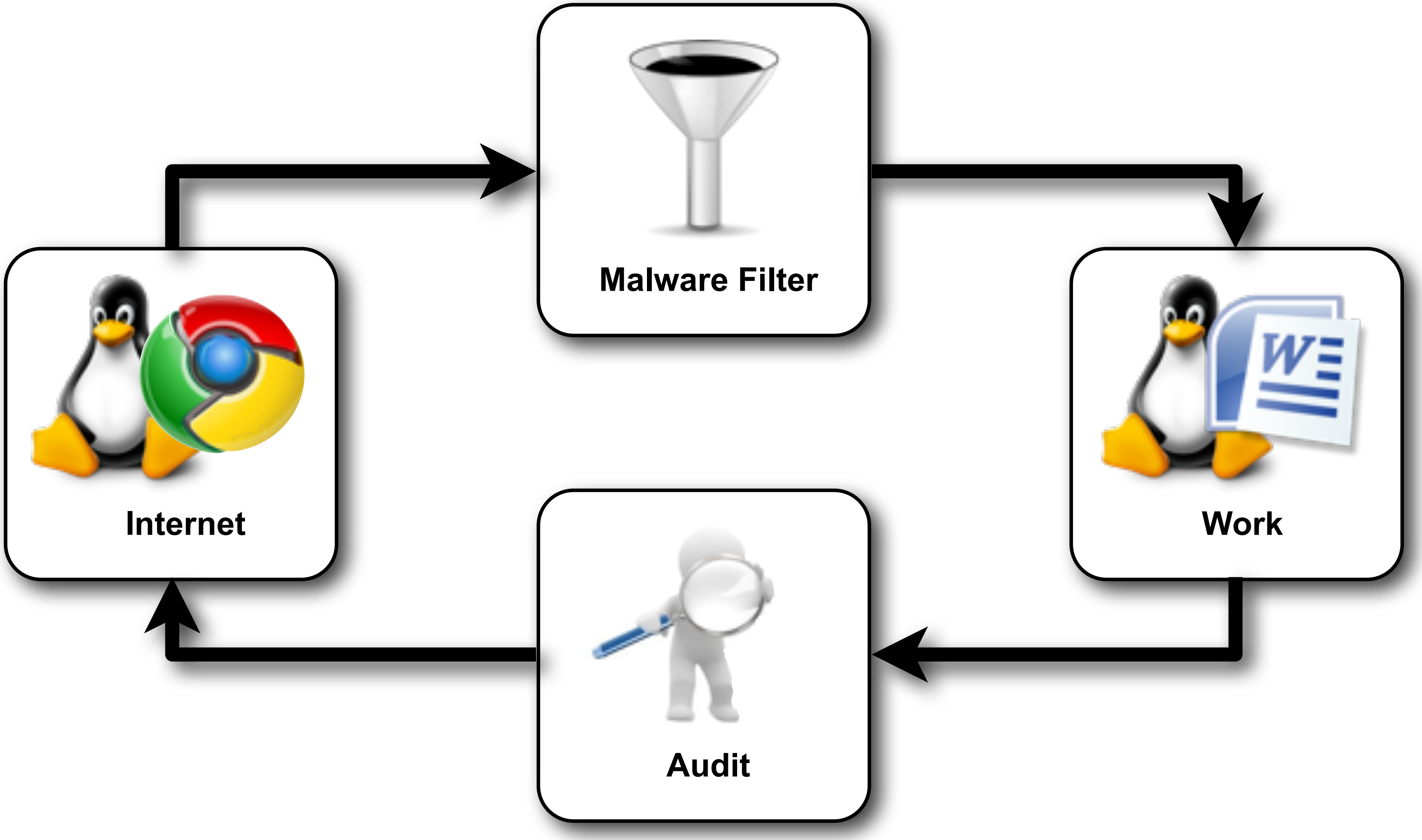
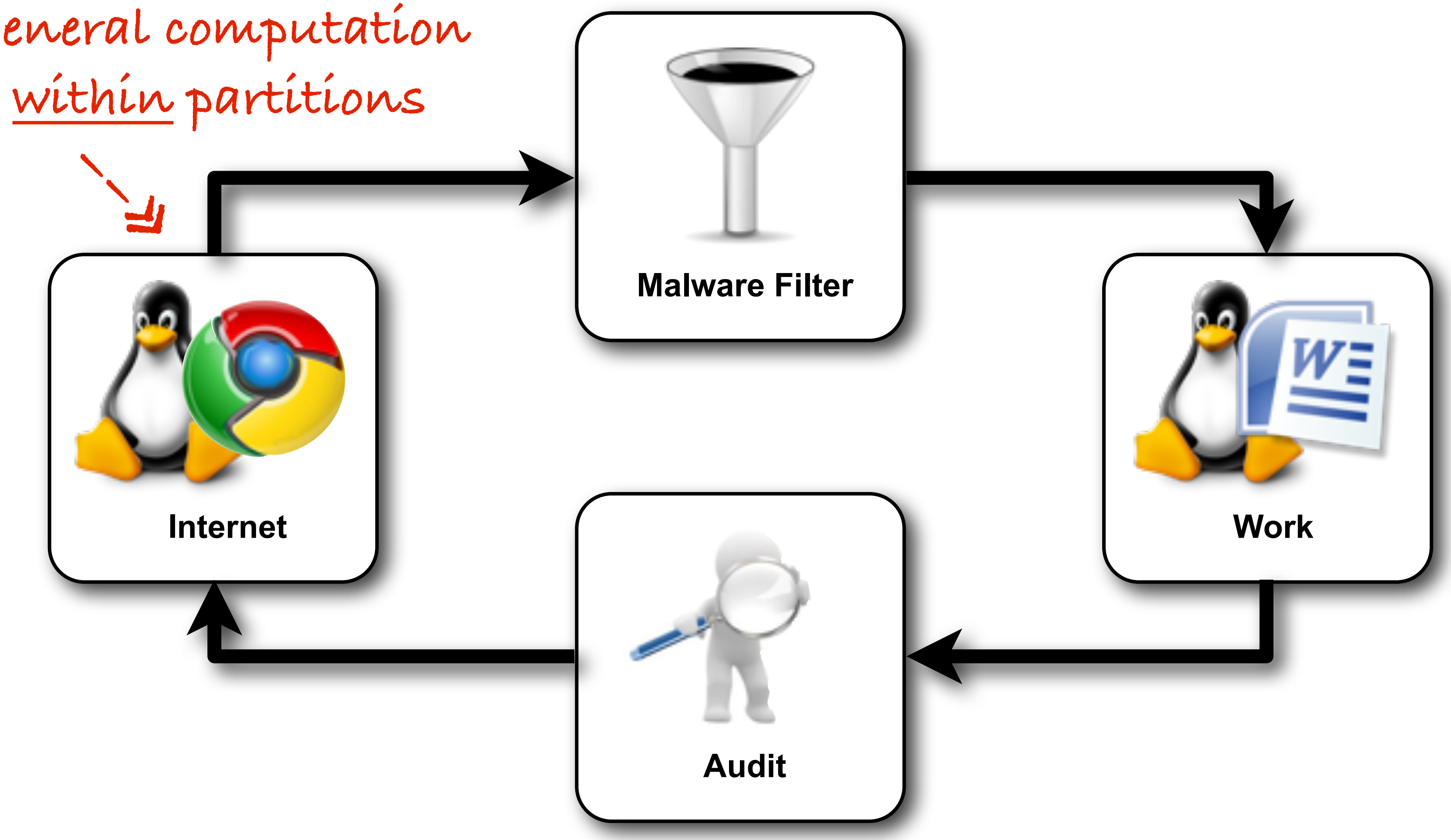
Information Flow Security (S&P 2013)



Information Flow Security (S&P 2013)

general computation
within partitions



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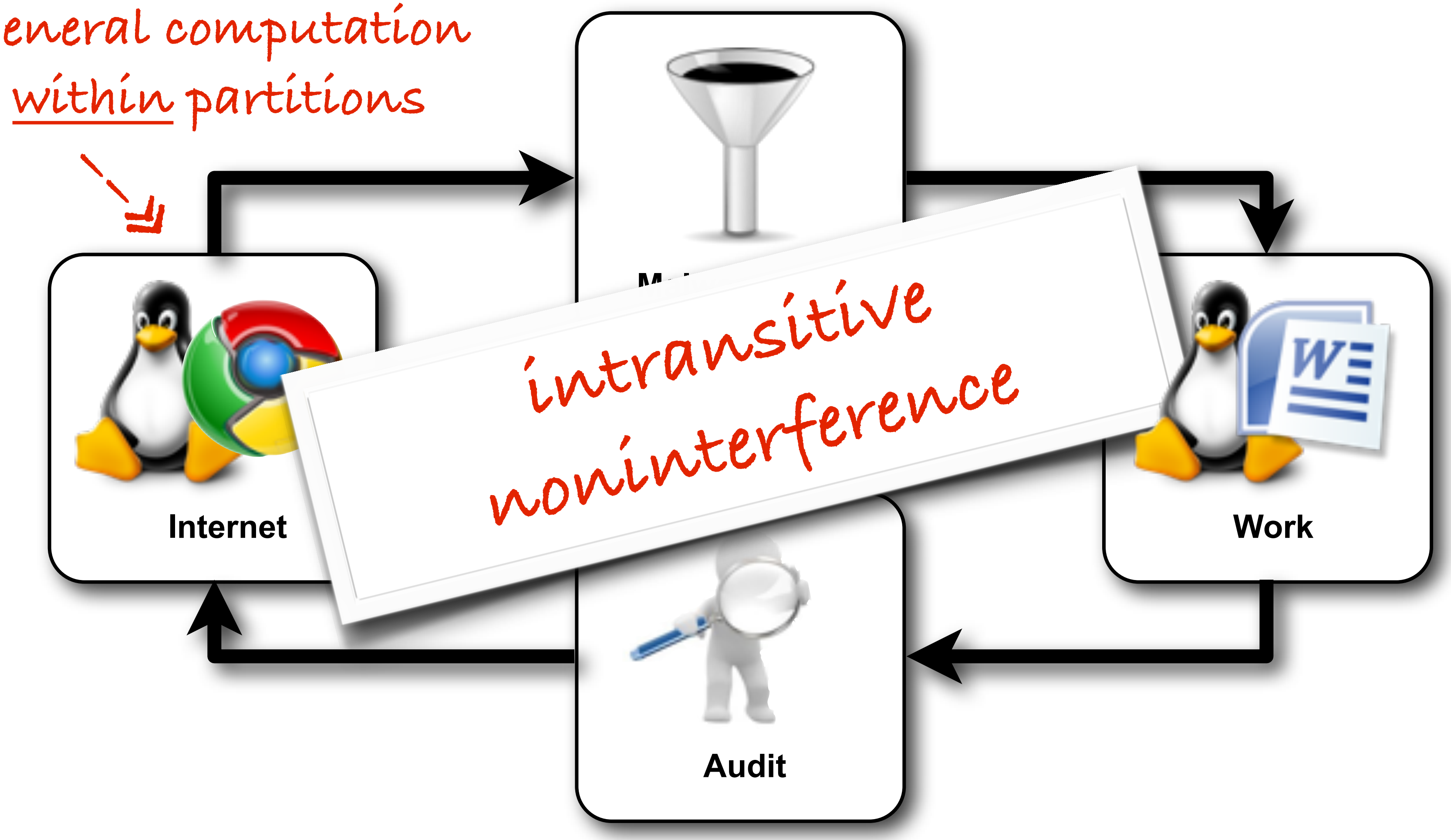
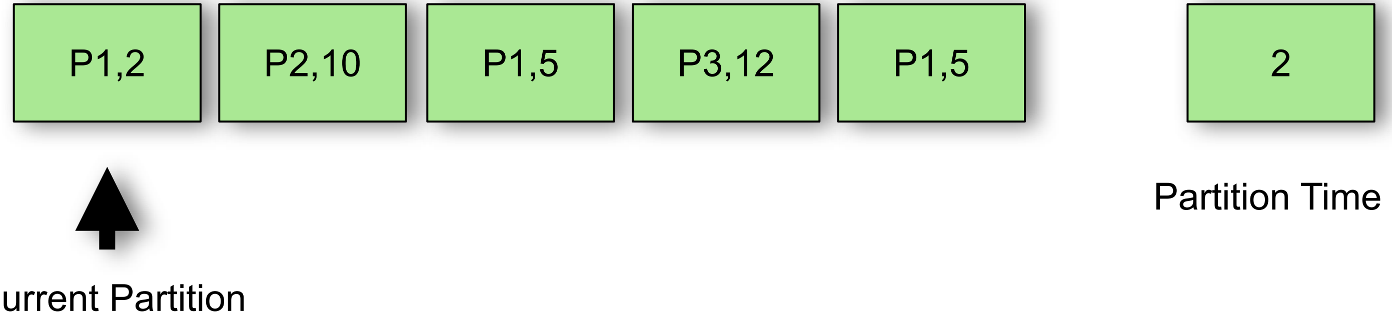


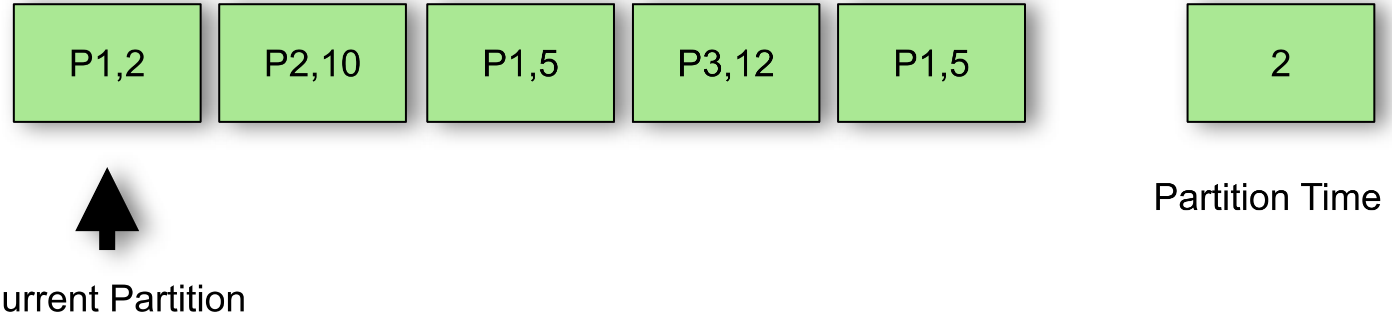
intransitive
noninterference

Only Kernel Change: Partition Scheduling



Only Kernel Change: Partition Scheduling

- Static round-robin schedule **between** partitions



P1,2

P2,10

P1,5

P3,12

P1,5

2

Partition Time

Current Partition

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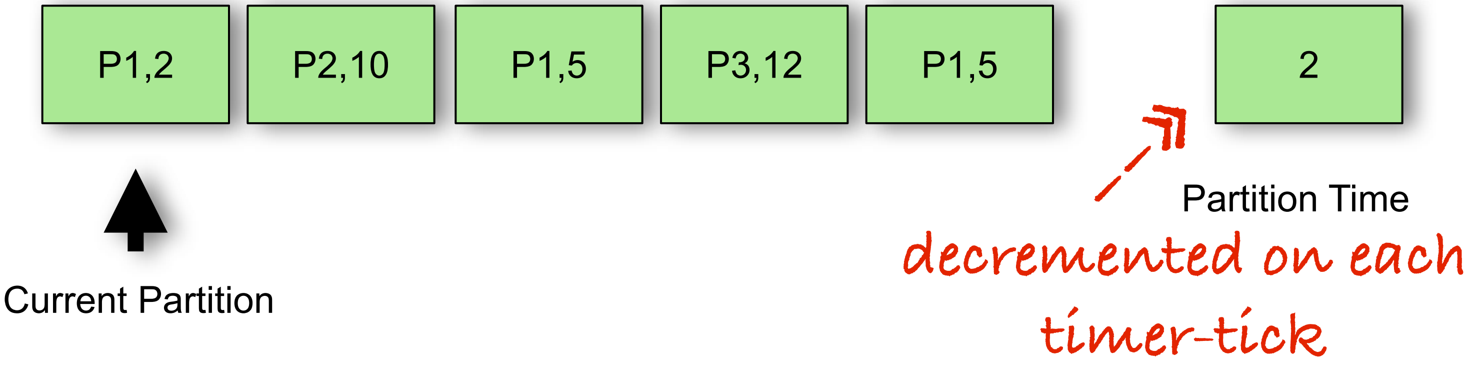

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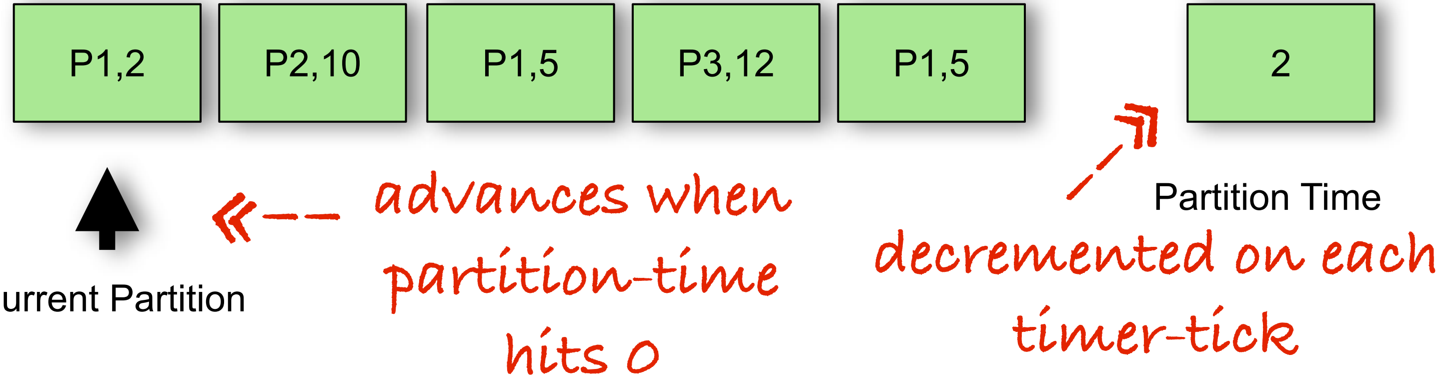

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Current Partition

advances when partition-time hits 0

Partition Time

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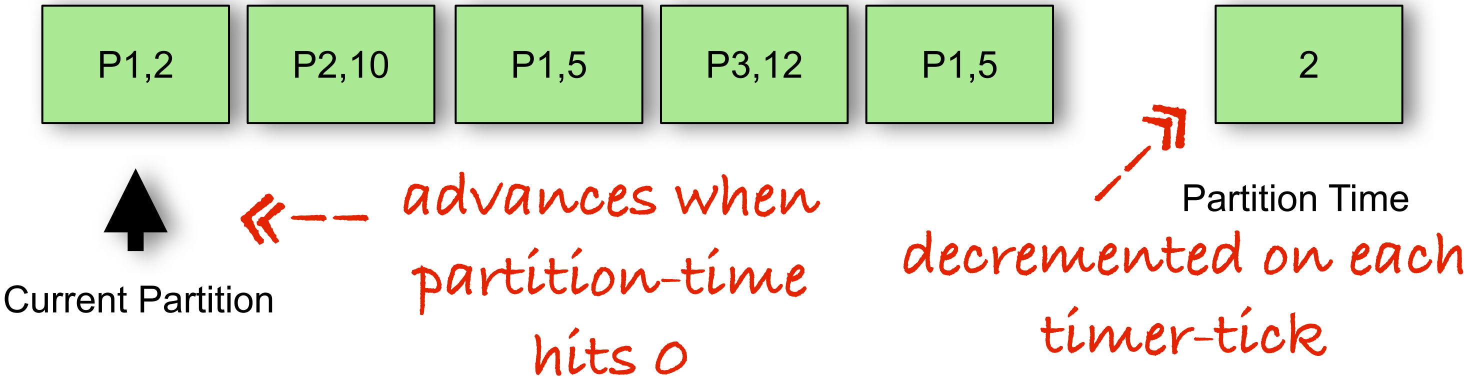

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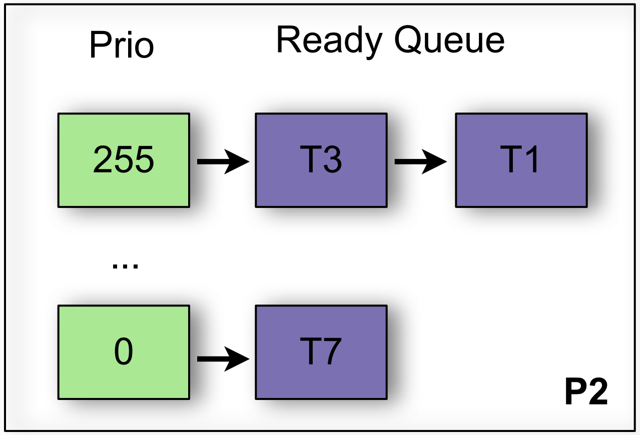
Current Partition

advances when partition-time hits 0

Partition Time

decremented on each timer-tick

- Priority-based scheduling **within** partitions
  - Choose the highest-priority thread that is ready
  - Run idle thread if none ready
  - Any other intra-partition scheduling algorithm possible



Problematic Kernel APIs

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not uncommon in high-assurance systems

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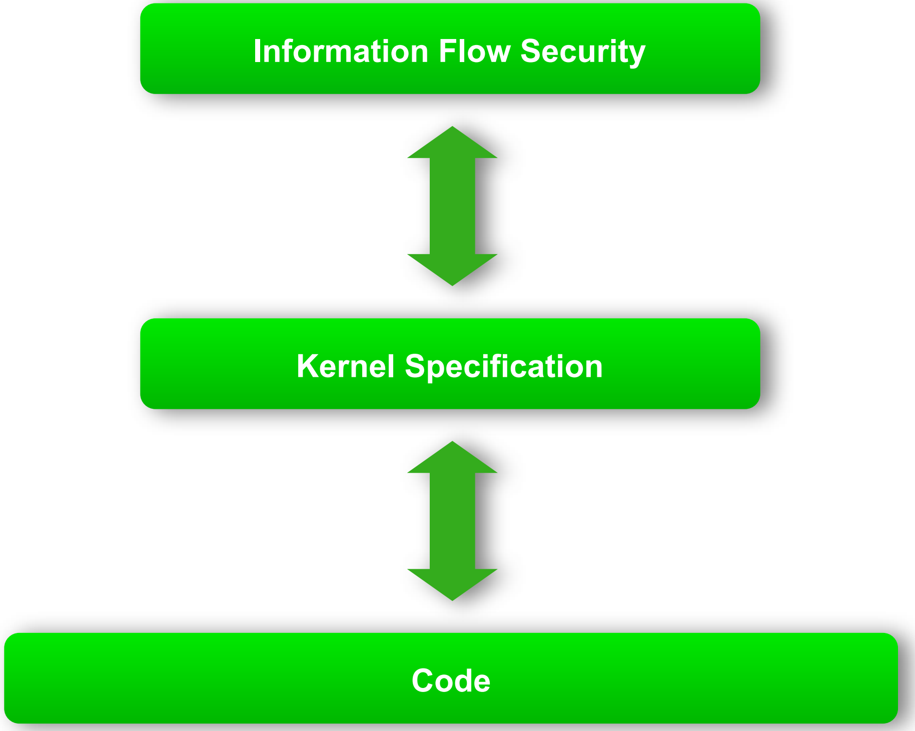
  - device

- Inter-partit
  - partition- destroyed

all kernel services available within partitions, besides async irq notification

not uncommon in high-assurance systems

Storage Channels



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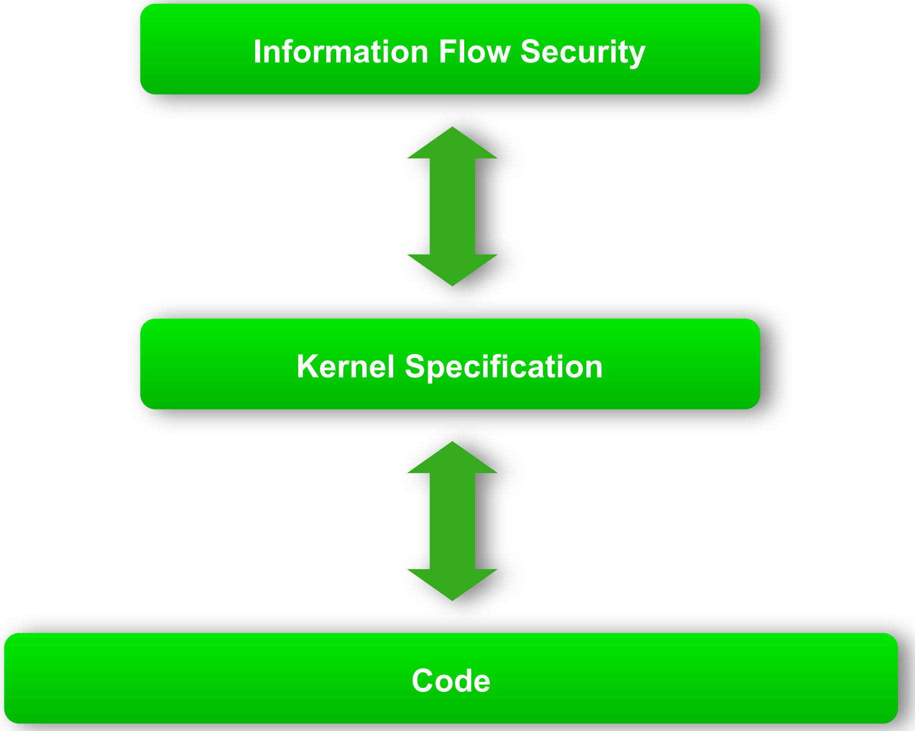

Information Flow Security

Kernel Specification

Code

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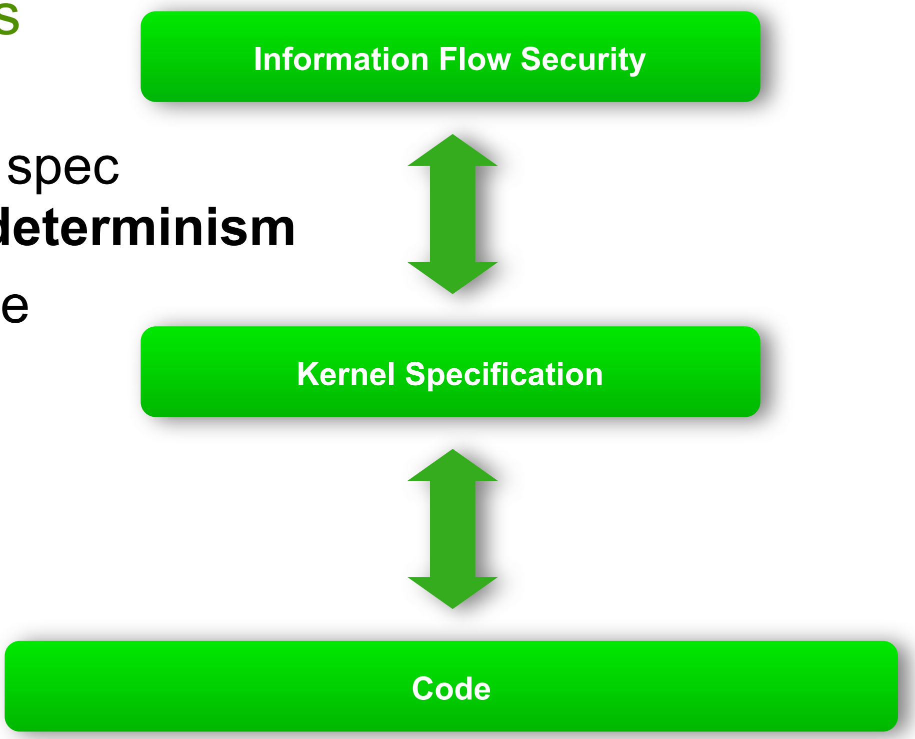

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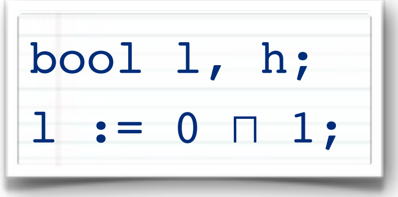
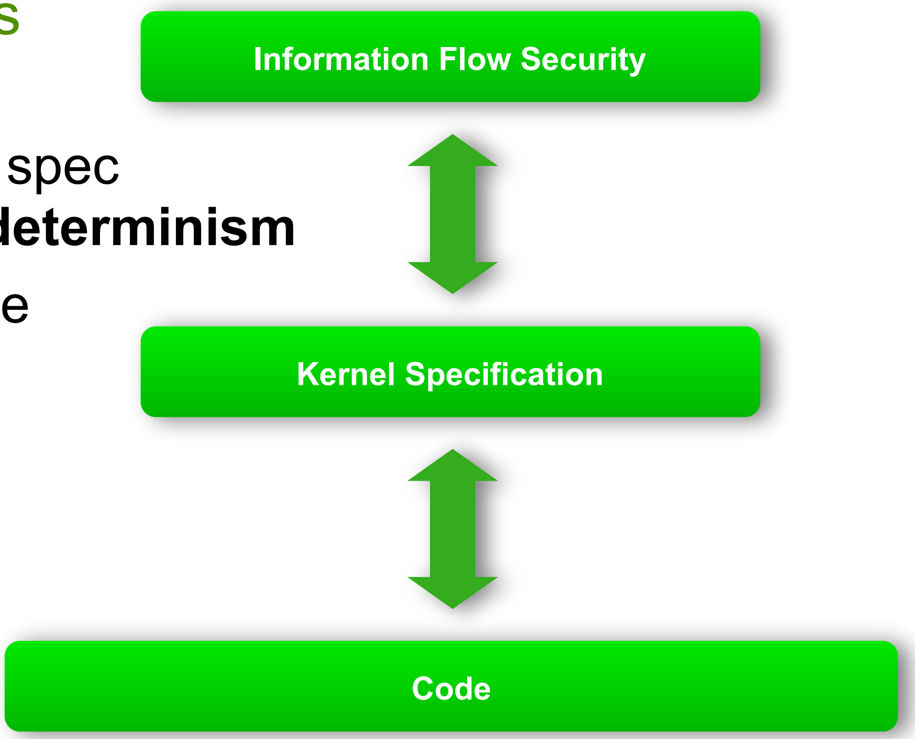


```
bool l, h;
l := 0 ⊓ 1;
```



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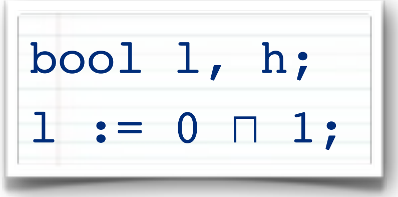

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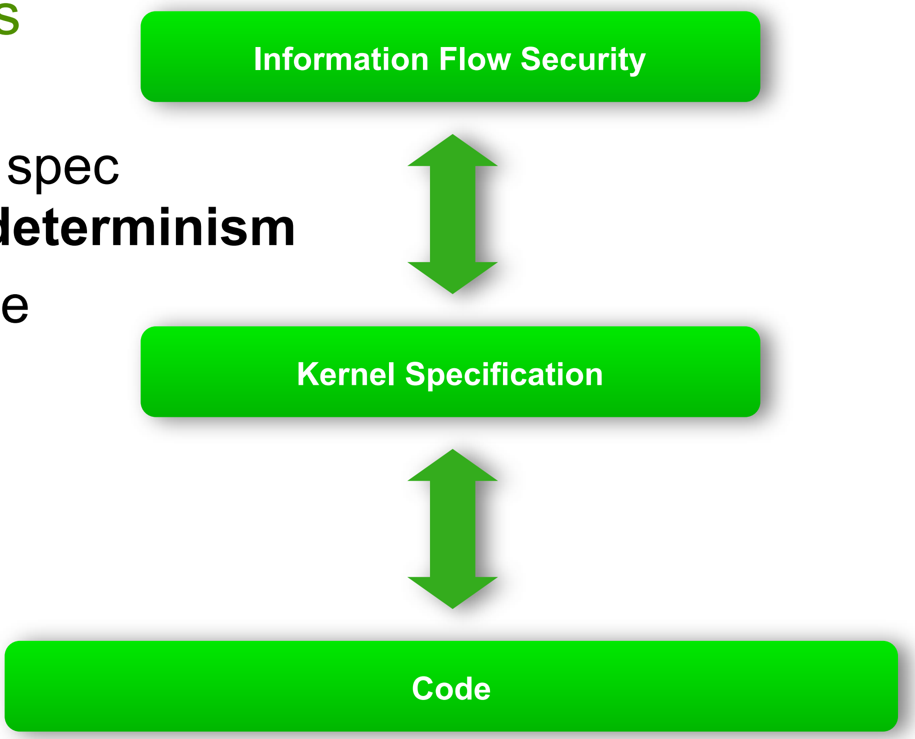

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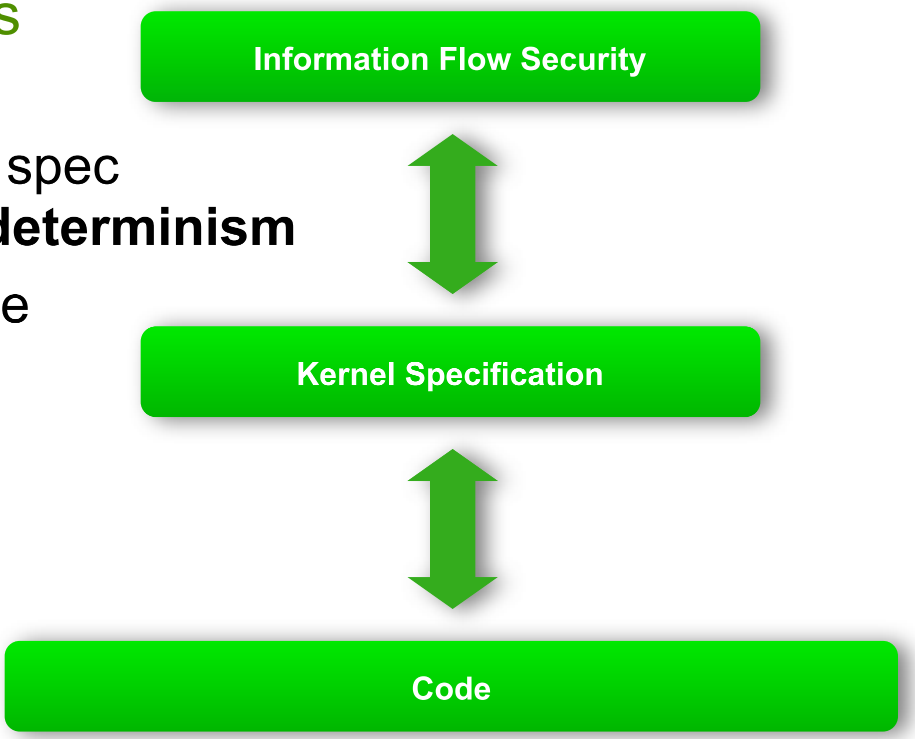
Information Flow Security

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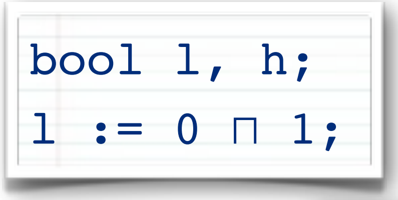
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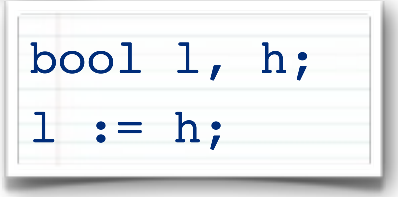
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bool l, h;
l := h;
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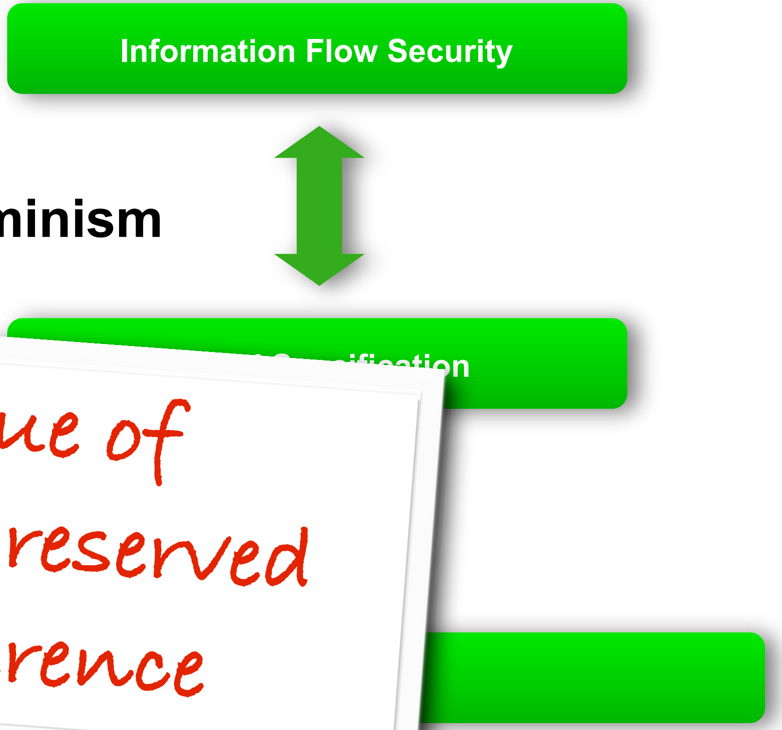

Information Flow Security

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is the value of refinement-preserved noninterference

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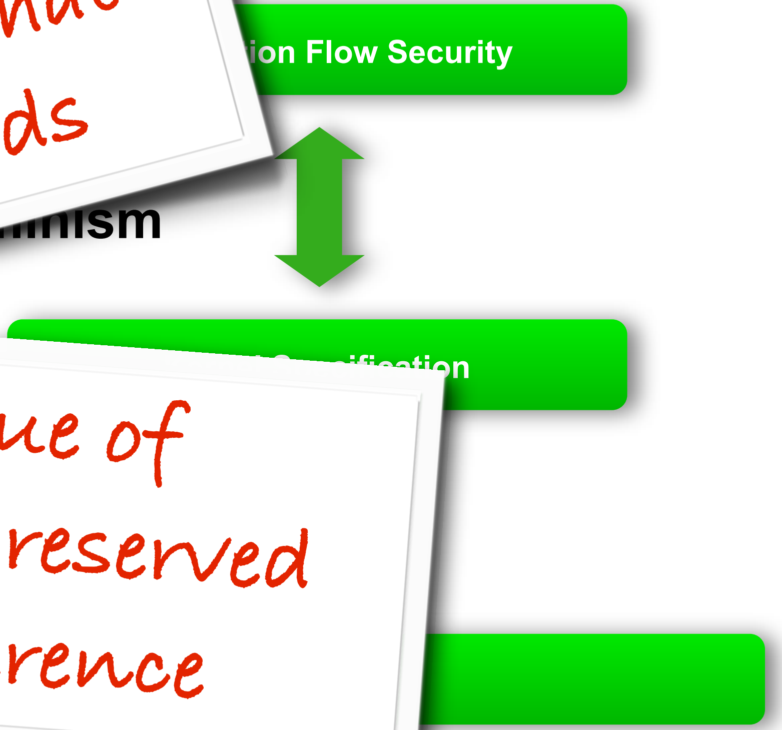

<u>not covered:</u> channels absent from spec that kernel never reads

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e.g. undocumented hardware APIs

```
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refinement-preserved noninterference

is refined by

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```

Timing Channels

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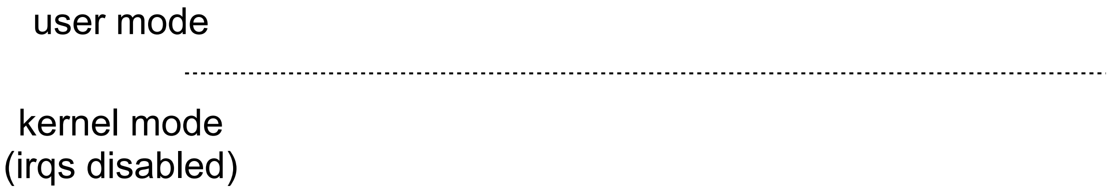

user mode

kernel mode
(irqs disabled)

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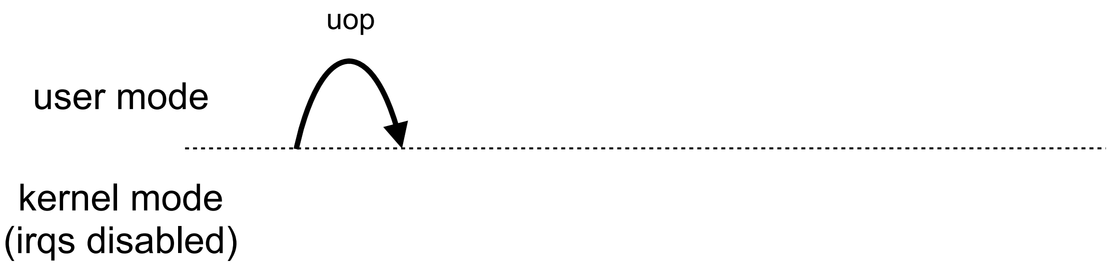

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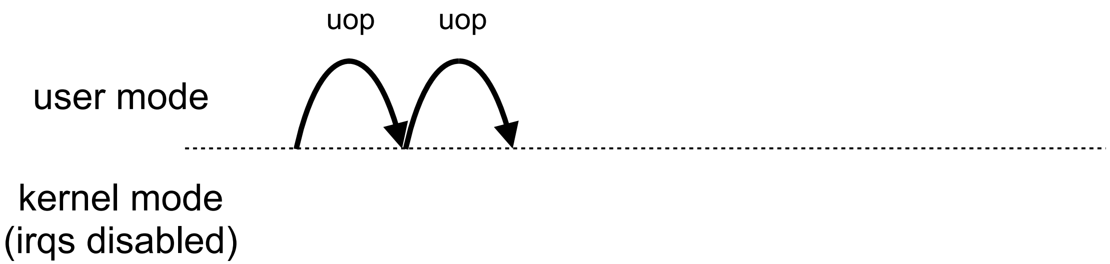

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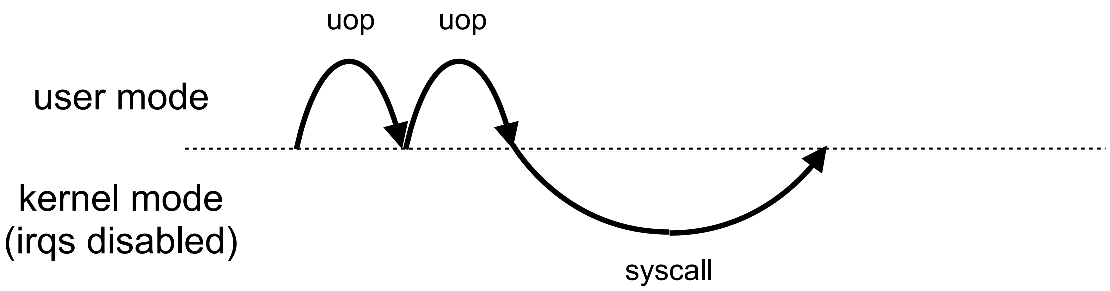

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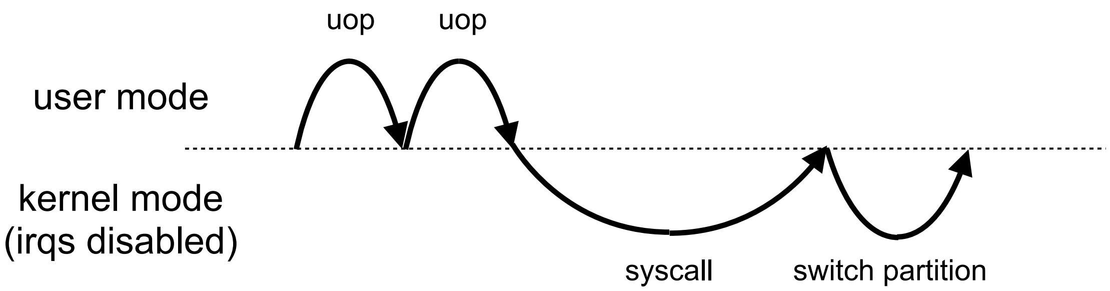

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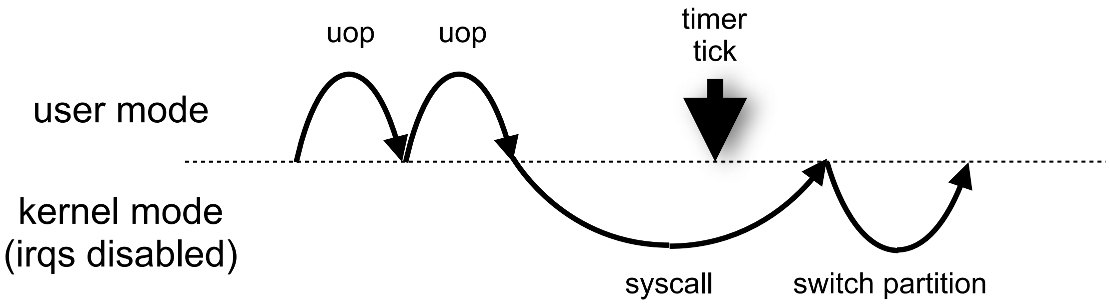

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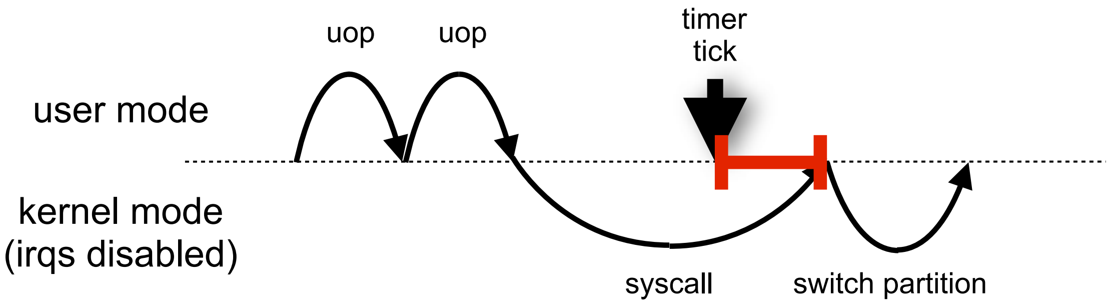

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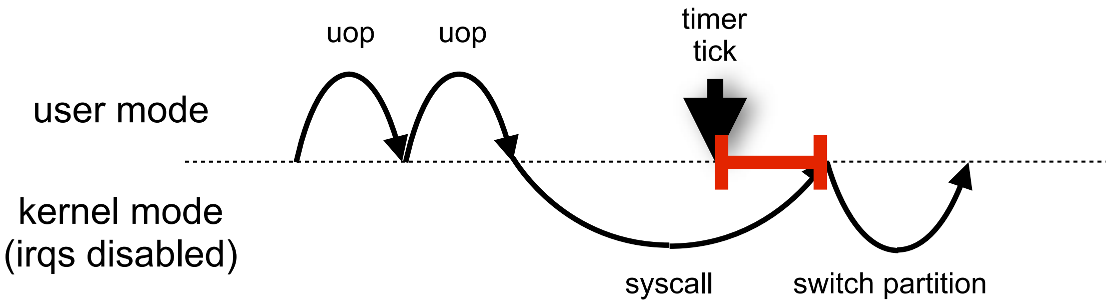

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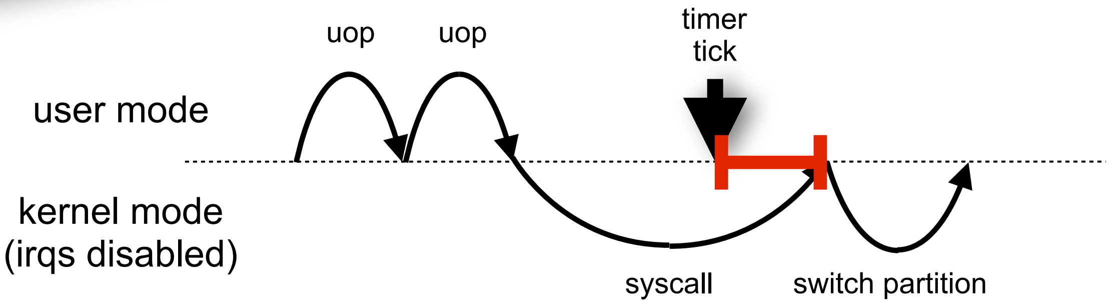

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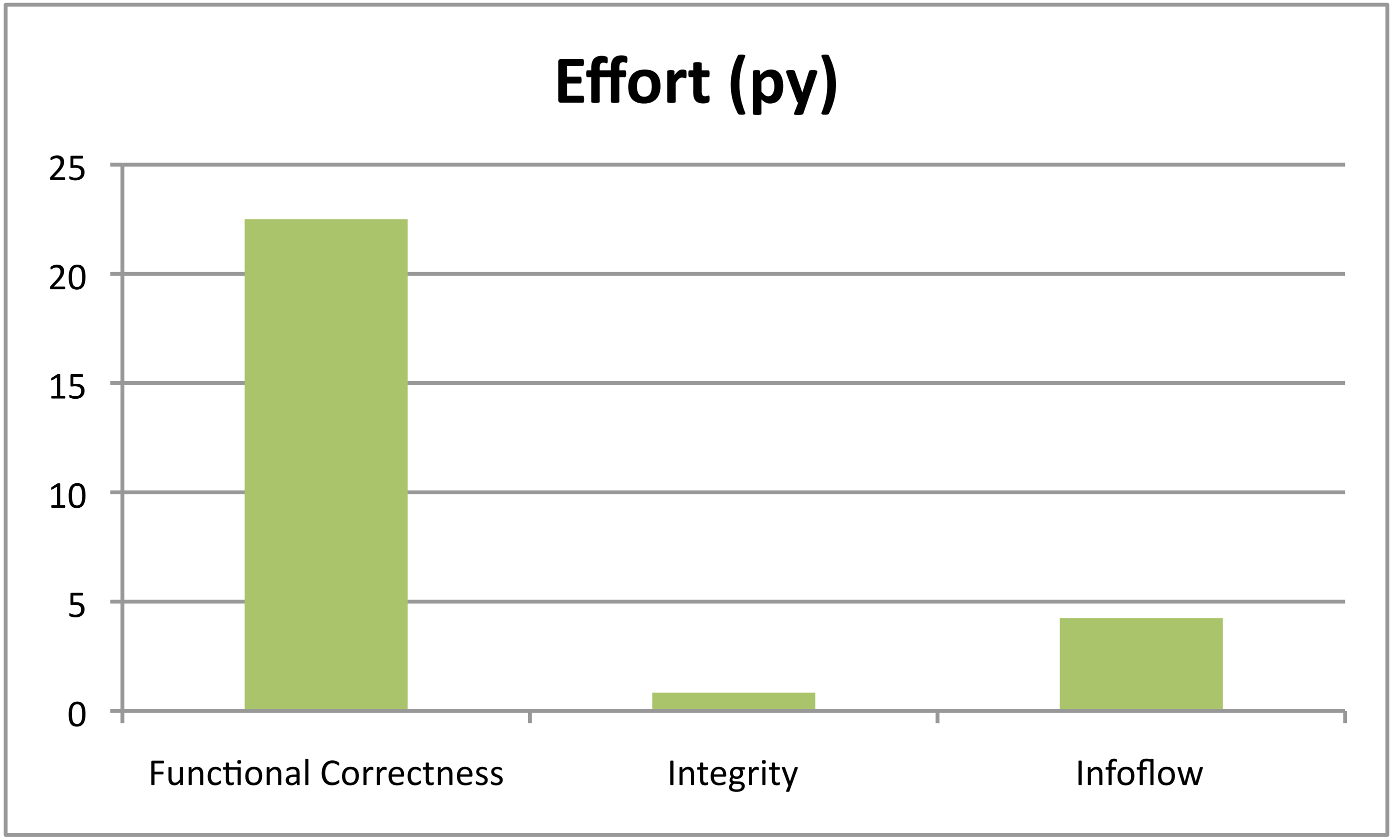
mitigation strategy depends on risk profile of deployment

- Others: caches, CPU temp. etc.

Lesson

- Functional correctness enables cheap security proofs



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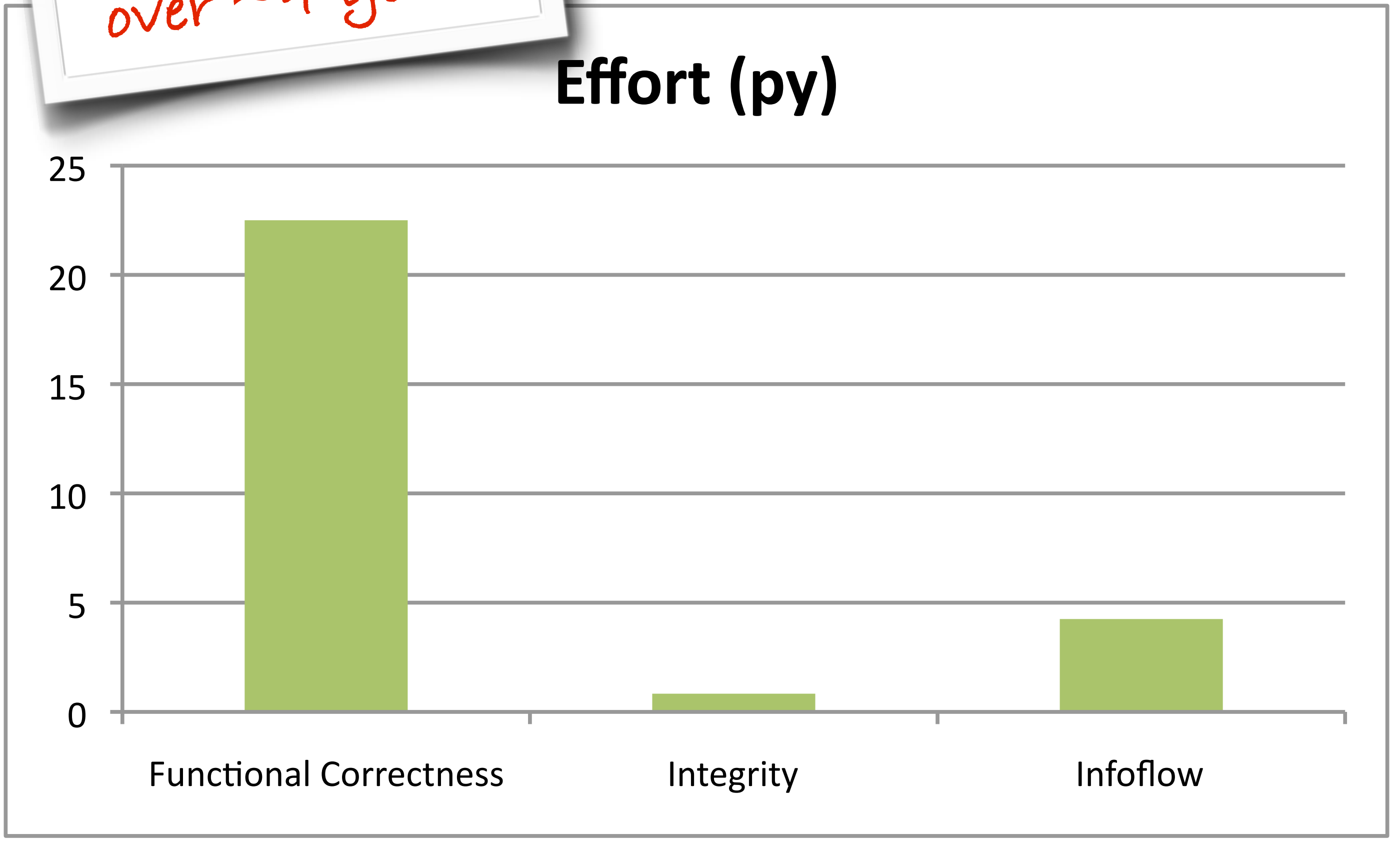
~6 people, over ~4 years



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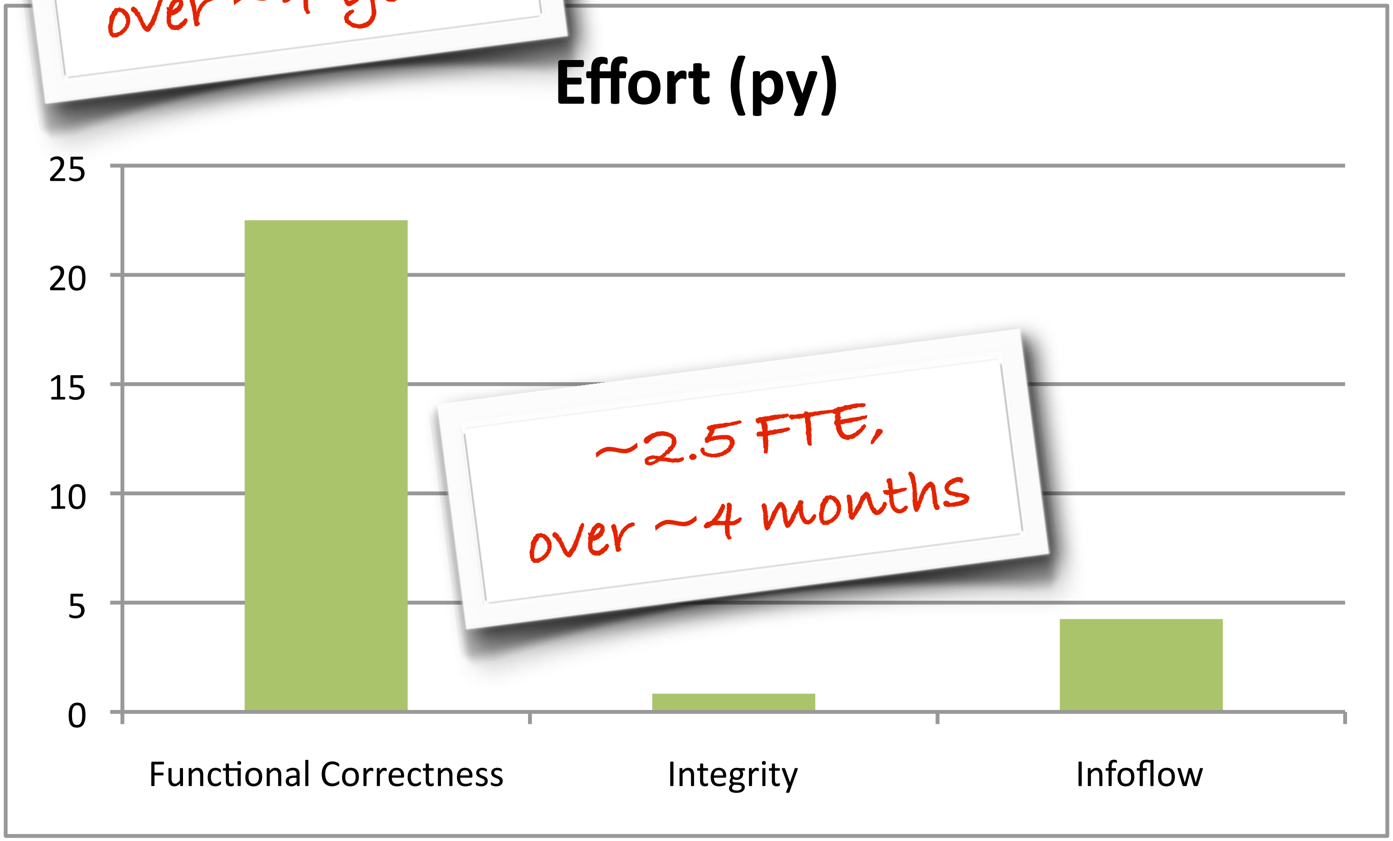

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~2.5 FTE, over ~4 months

Lesson

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~2.5 FTE,
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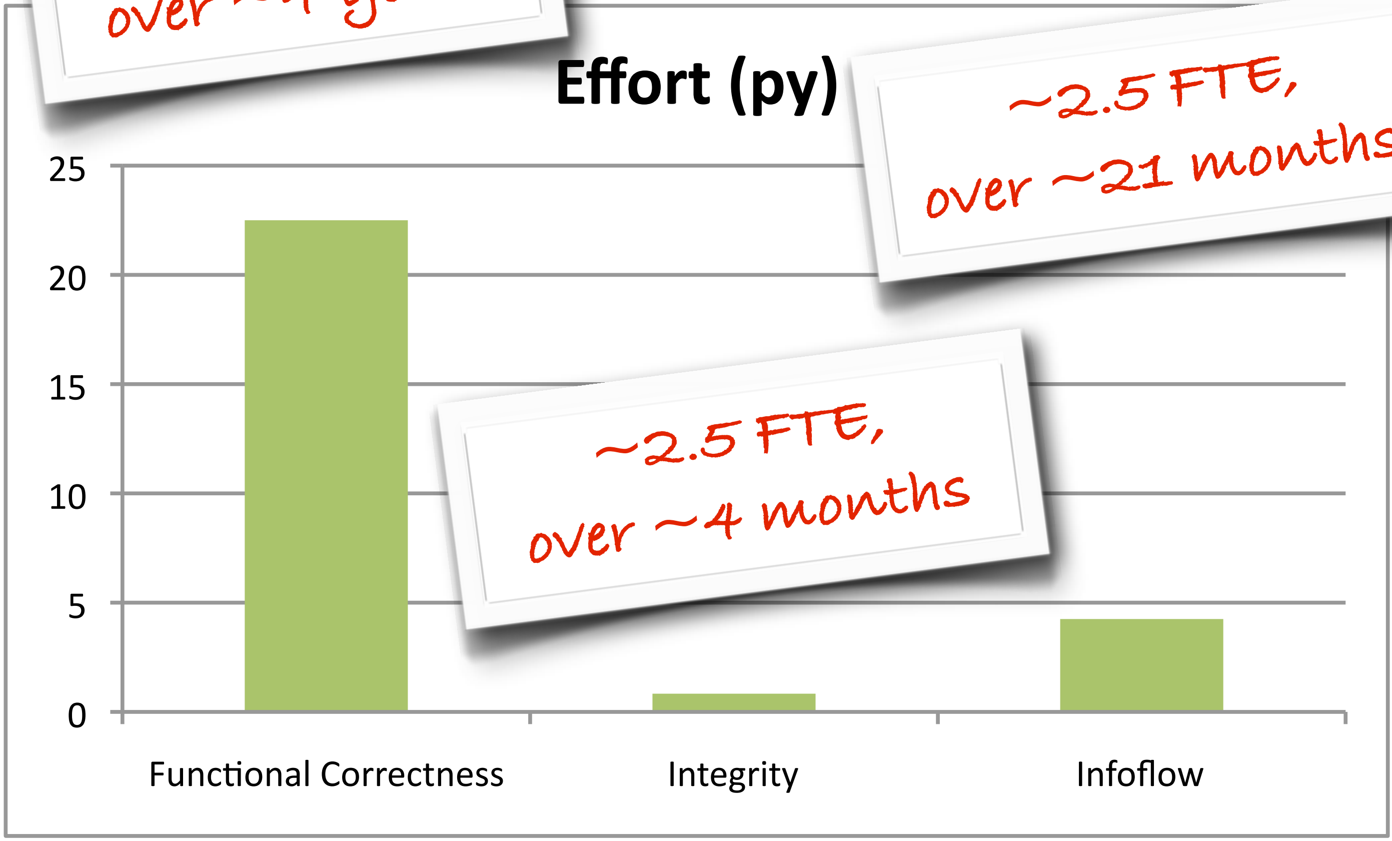


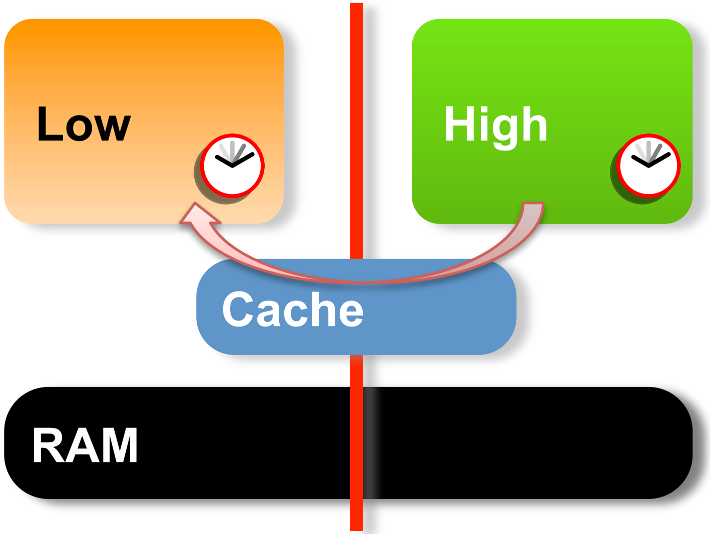
Analysing Timing Channels (CCS 2014)

- Formal verification framework has no explicit concept of time
- Modern architectures too complex to accurately model timing
- Use experimental approach:
  - Implement timing channels exploits and mesures
  - Sound information theoretic approach to analysis

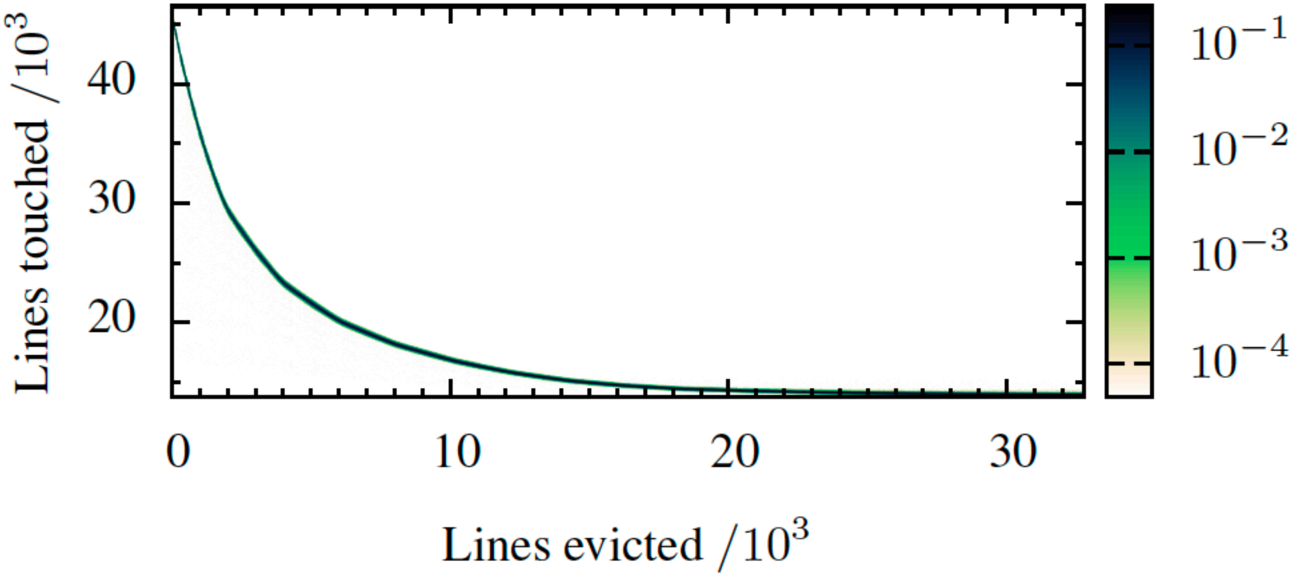
- Objective:
  - Understand and quantify kernel-relevant timing channels
  - Develop minimal mechanisms to mitigate channels
    - Must not compromise seL4's generality and verifiability
    - Must not degrade performance when timing channels don't matter

Example: cache contention channel

- Partitions compete for space in the cache
- Low partition can observe High partition’s cache footprint



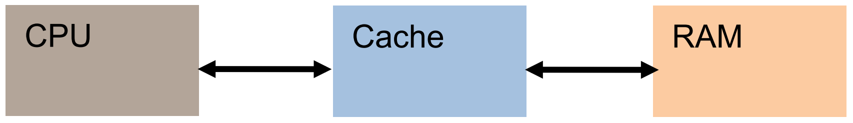
Unmitigated Cache Channel

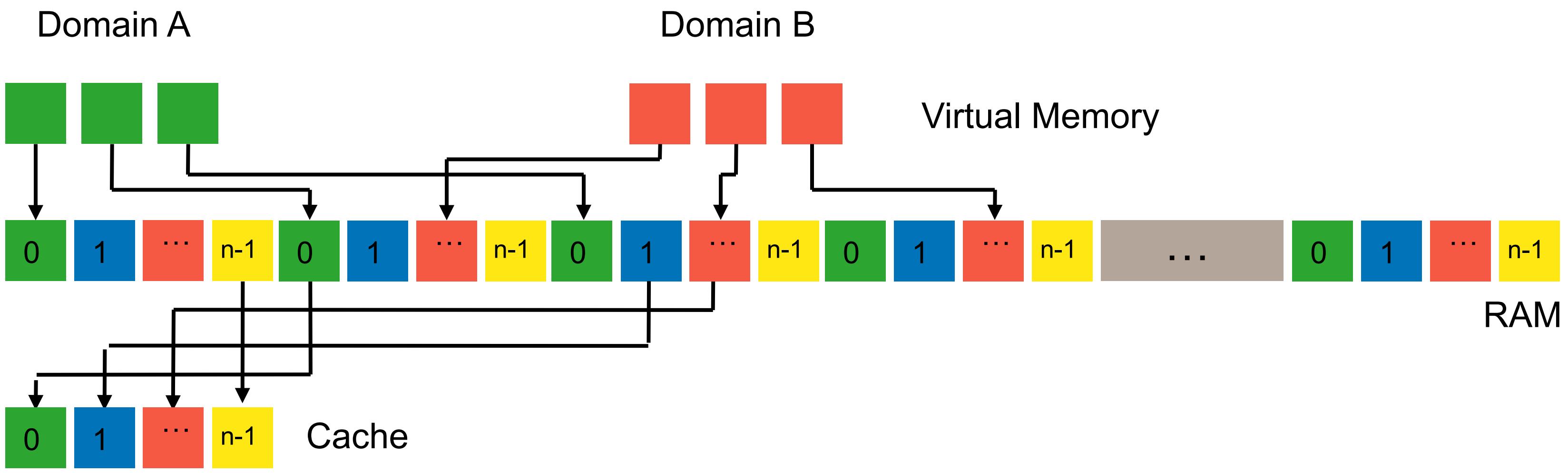


- Cache channel measures on the Exynos4412 (ARMv7, Cortex-A9)
  - Estimated bandwidth: 2,350 b/s
  - Each column is 1,000 samples
  - This graph captures 4.77 TiB of uncompressed data

Cache Colouring

Partition cache between different security domains to prevent cache interference





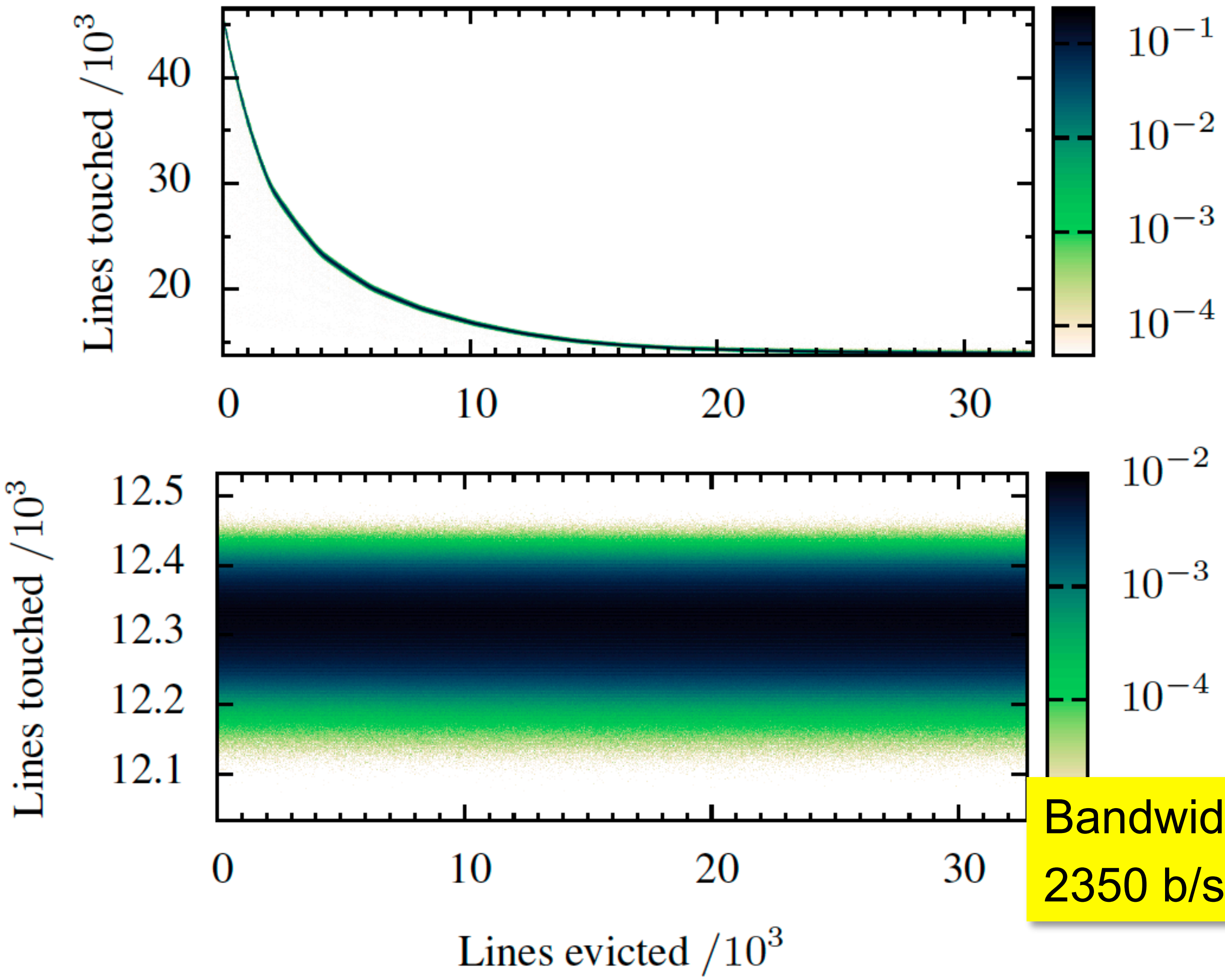
Allocation of colours to domains implemented outside kernel

- Existing kernel memory allocation mechanism already sufficient

Kernel modified to duplicate its own code on-demand

- Each partition has its own copy, preventing i-cache interference

Effectiveness of Cache Colouring



Bandwidth:
2350 b/s → 27 b/s

Timing Channel Observations

- Empirical measurement is essential
  - coupled with sound information theory for analysis
- Has revealed unexpected channels
  - cycle counter influenced by cache misses, branch mispredicts
- Well-designed kernel mechanisms can be effective
  - ... but manufacturers are working against us

OS DESIGN FOR SECURITY

OS Design for Security

- Minimise kernel code
  - can bypass all security, inherent part of TCB
- How?:
  - generic mechanisms
  - no policies, only mechanisms
  - mechanisms as simple as possible
  - exclude all code that doesn't need to be privileged to support secure systems
  - minimise covert channels
    - no global namespaces, or absolute time

Security and Concurrency

- Avoid concurrent access to security state
  - leads easily to security vulnerabilities
- Time of Check-to-Time-of-Use (TOCTTOU)
  - common in privileged reference monitors

```
if (access(“file”, W_OK) != 0) {
   exit(1);
}

fd = open("file", O_WRONLY);
write(fd, buffer, sizeof(buffer));
```

```
symlink("/etc/passwd", "file");
```

  - Make rights checks atomic with accesses
  - Why most system-call wrappers don’t work

Unexpected Concurrency

- Example: FreeBSD Capsicum vulnerability
  - openat() with paths involving multiple "..”s
  - activity can occur between each ".." lookup
  - second process races with first to ensure each ".." lookup succeeds, using renameat()
  - allows escaping of sandboxes
- Solutions:
  - complicate the lookup code
  - disallow multiple "..”s in pathnames (simpler)
- Second solution was chosen

Designing Secure Mechanisms

- Simplify security mechanisms
  - Because they are hard enough to get right in the first place
- Ensure mechanisms are well-defined
  - make policy and granting authority explicit
- Flexibility to support various uses
  - support explicit delegation of authority
- Design for verifiability
  - minimise implementation complexity

Example: seL4

- Simple AC mechanism: capabilities
  - supports least privilege, decideable
- No in-kernel concurrency
  - single kernel stack, poll for IRQs
- Formal proof of implementation correctness
- Formal proof that design (and so code) enforces relevant security properties:
  - integrity (ITP, 2011)
  - confidentiality (S&P, 2013)

QUESTIONS?

BEER O’CLOCK?