Secure Operating Systems

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Overview

- *Operating systems security overview*
- Types of secure systems
- Security policies
- Security mechanisms
- Design principles
- OS security verification
- OS design for security

Secure Operating System

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- Provides for secure execution of applications
- Must provide security policies that support the users' security requirements
- Must enforce those security policies
- Must be safe from tampering etc.

Security Policies

- Security policy
  - Specifies *allowed* and *disallowed states* of a system
  - OS needs to ensure that no disallowed state is ever entered
  - OS *mechanisms* prevent transitions from allowed to disallowed states
- Security policy needs to identify the *assets* to be secure
  - For computer security, assets are typically *data*
- Perfect security is generally unachievable
  - Need to be aware of *threats*
  - Need to understand what *risks* can be tolerated

Security Mechanisms

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- Used to enforce security policy
  - Computer access control (login authentication)
  - Operating system file access control system
  - Controls implemented in tools
- Example:
  - Policy: only accountant can access financial system
  - Mechanism: on un-networked computer in locked room with only one key
- A *secure system* provides mechanisms that ensure that violations are
  - Prevented
  - Detected
  - Recovered from

Trust

- Systems always have *trusted entities*
  - Hardware, operating system, sysadmin
- Totally of trusted entities is the *trusted computing base* (TCB)
  - The part of the system that can circumvent security
- A *trusted system* can be used to process security-critical assets
  - Gone through some process ("*assurance*") to establish its trustworthiness
  - Should really be called *trustworthy system*
- *Trusted computing*:
  - Provides mechanisms and procedures for trusted systems
  - In practice usually refers to TCG mechanisms for secure boot, encryption etc

Trusted Computing Base

- TCB: *The totality of protection mechanisms within a computer system — including hardware, firmware and software — the combination of which is responsible for enforcing a security policy*

  [RFC 2828]

  A TCB consists of one or more components that together enforce a unified security policy over a product or system

  The ability of the TCB to correctly enforce a security policy depends solely on the mechanisms within the TCB and on the correct inputs by system administrative personnel or parameters related to the security policy

Covert Channels (Side Channels)

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- Information flow that is not controlled by a security mechanism
  - Security requires *absence of covert channels*
- Two types of covert channels
  - Covert *storage* channel uses an attribute of a shared resource
    - Typically meta data, like existence or accessibility of an object
    - Global names create covert storage channels
    - In principle subject to access control
    - A sound access-control system should be *free* of covert channels
  - Covert *timing* channel uses temporal order of accesses to shared resource
    - Outside access-control system
    - Difficult to reason about
    - Difficult to prevent

Covert Timing Channels

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- Created via shared resource whose behaviour can be monitored
  - Network bandwidth
  - CPU load
  - Response time
  - Locks
- Requires access to a time source
  - Real-time clock
  - Anything else that allows unrelated processes to synchronise
  - Preventable by perfect virtualisation?
- Critical issue is bandwidth
  - In practice, the damage is limited if the bandwidth is low
    - e.g DRM doesn't care about low-bandwidth channels
  - Beware of amplification
    - e.g leaking of passwords

Establishing Trustworthiness

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- Process to show *TCB is trustworthy*
- Two approaches
  - *Assurance* (systematic evaluation and testing)
  - *Formal verification* (mathematical proof)
- *Certification* confirms process was successfully concluded

Assurance

- Process for *bolstering* (substantiating or specifying) trust
  - Specifications
    - Unambiguous description of system behaviour
    - Can be formal (mathematical model) or informal
  - Design
    - Justification that it meets specification
    - Mathematical translation of specification or compelling argument
  - Implementation
    - Justification that it is consistent with the design
    - Mathematical proof or code inspection and rigorous testing
    - By implication must also satisfy specification
  - Operation and maintenance
    - Justification that system is used as per assumption in specification
- Assurance does not *guarantee* correctness or security!

Assurance: Orange Book

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US Department of Defence "Orange Book" [DoD 86]:

- Officially the *Trusted Computing Systems Evaluation Criteria* (TCSEC)
- Defines security classes
  - D: minimal protection
  - C1-2: discretionary access control (DAC)
  - B1-B3: mandatory access control (MAC)
  - A1: verified design
- Designed for military use
- Systems can be certified to a certain class
  - Very costly, hence only available for big companies
  - Most systems only certified C2 (essentially Unix-style security)
- Superseded by *Common Criteria*
  - Orange book no longer has any official standing
  - However, still an excellent reference for security terminology and rationale

Assurance: Common Criteria

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Common Criteria for IT Security Evaluation [ISO/IEC 15408]:

- ISO standard, developed out of Orange Book and other approaches
  - US, Canada, UK, Germany, France, Netherlands
  - For general use (not just military, not just operating systems)
- Unlike Orange Book, doesn't prescribe specific security requirements
  - Evaluates quality assurance used to ensure requirements are met
- *Target of evaluation* (TOE) evaluated against *security target* (ST)
  - ST is statement of desired security properties
  - Based on *protection profiles* (PPs) — generic sets of requirements
    - Defined by “users” (typically governments)
- Seven *evaluation assurance levels* (EALs)
  - Higher levels imply more thorough evaluation (and higher cost)
  - *Not* necessarily better security
- Details later

Formal Verification

- Process of mathematical proof of security properties
- Mased on a mathematical *model* of the system
- Two Parts:
  - Proof that *model satisfies security requirements*
    - Generally difficult, except for very simple models
  - Proof that *code implements model*
    - Proving theorems showing correspondence
    - Even harder, feasible only for few 1000 LOC
    - Hardly ever done
- Note: *model checking* (static analysis) is not sufficient
  - Shows presence or absence of certain properties of code
    - Uninitialised variables, array-bounds, null-pointer de-ref.
  - Does not prove implementation correctness

Summary

- Computer security is complex
  - Depends on many aspects of computer system
- Policy defines security, mechanisms enforce security
- Important to consider:
  - What are the assumptions about threats and trustworthiness?
  - Incorrect assumptions ⇒ no security
- Security is never absolute
  - Given enough resources, mechanisms can be defeated
  - Important to understand limitations
  - Inherent tradeoffs between security and usability
- Human factors are important
  - People make mistakes
  - People may not understand security impact of actions
  - People may be less trustworthy than thought

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Secure Systems Classification

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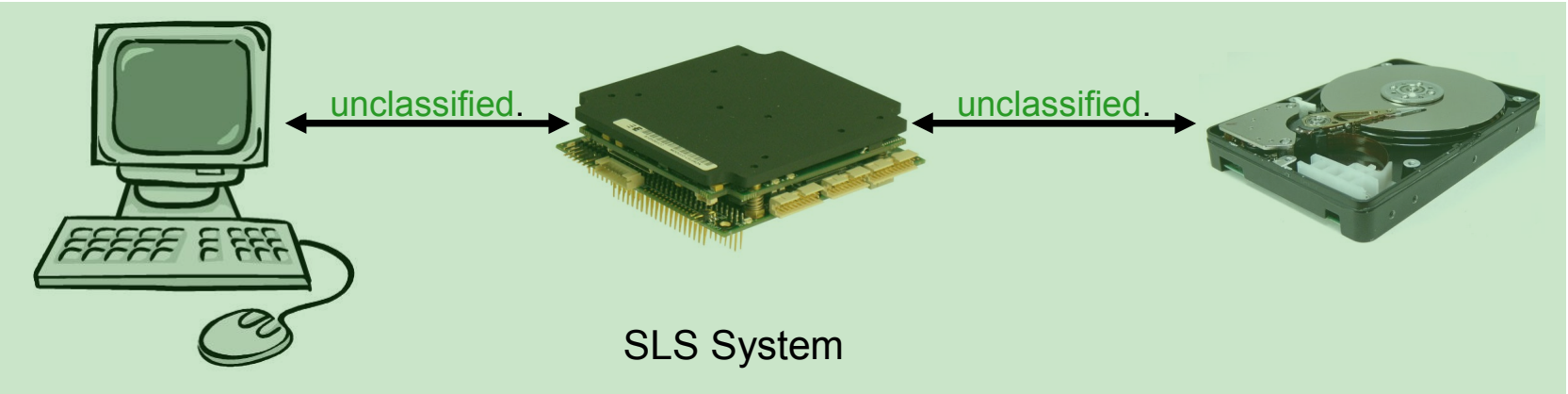
- Based on Orange Book terminology
  - Assumes military-style security problem
  - Data of different security classifications
  - System must ensure that classification is enforced
- Classifies systems based on the kind of data they can deal with
  - *Single-level secure* (SLS) system
  - *Multiple single-level secure* (MSL) system
  - *Multi-level secure* (MLS) system
- Basis of *multiple-independent levels of security* (MILS) architecture

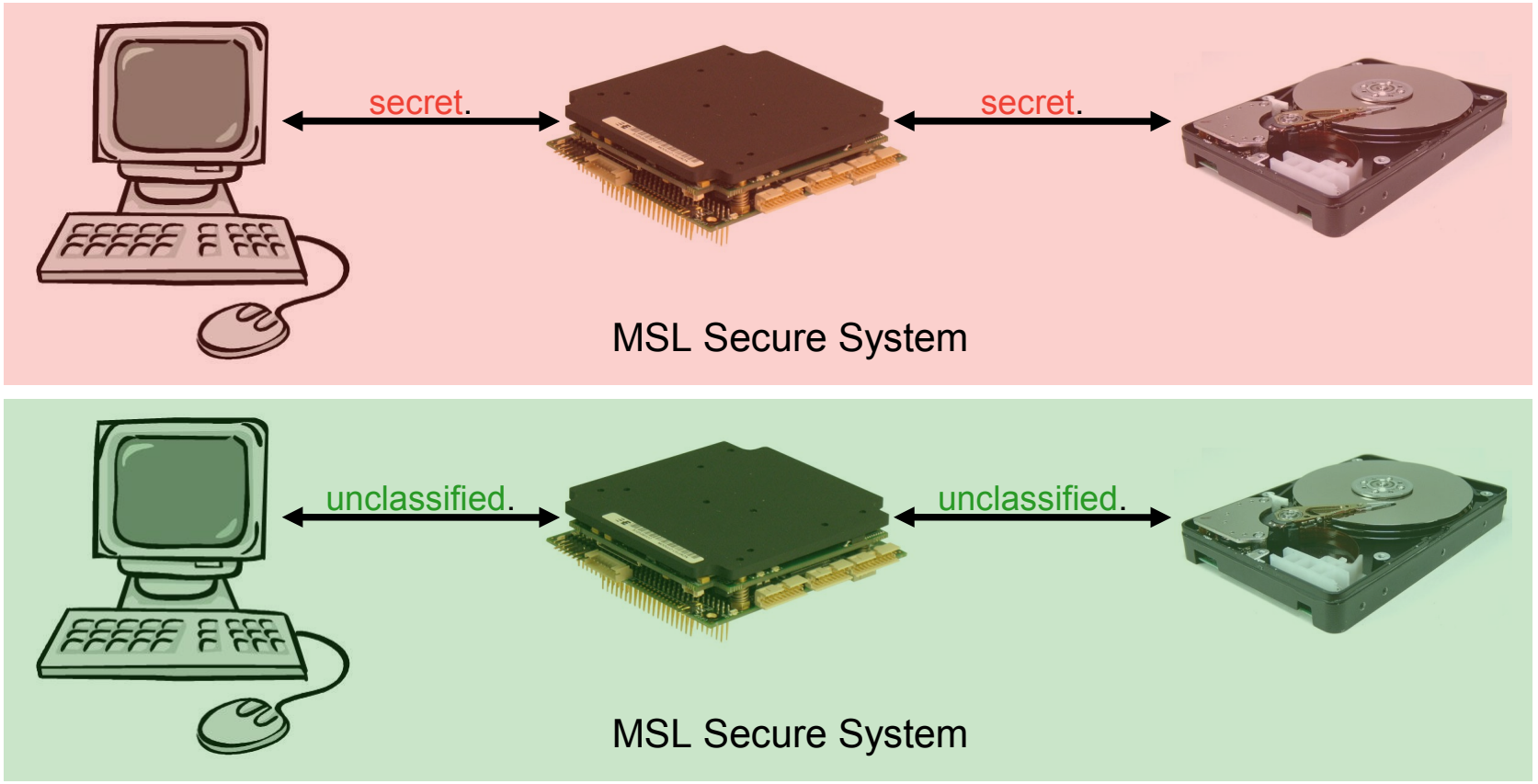
Single-Level Secure (SLS) System

- Suitable only for processing data of one particular security level
  - generally the lowest, i.e. unclassified



Multiple Single-Level (MSL) Secure System

- System suitable for processing data of several security levels
  - only one security level at a time, up to some limit
- Multiple instances used, each one as a SLS system



Multi-Level Secure (MLS) System

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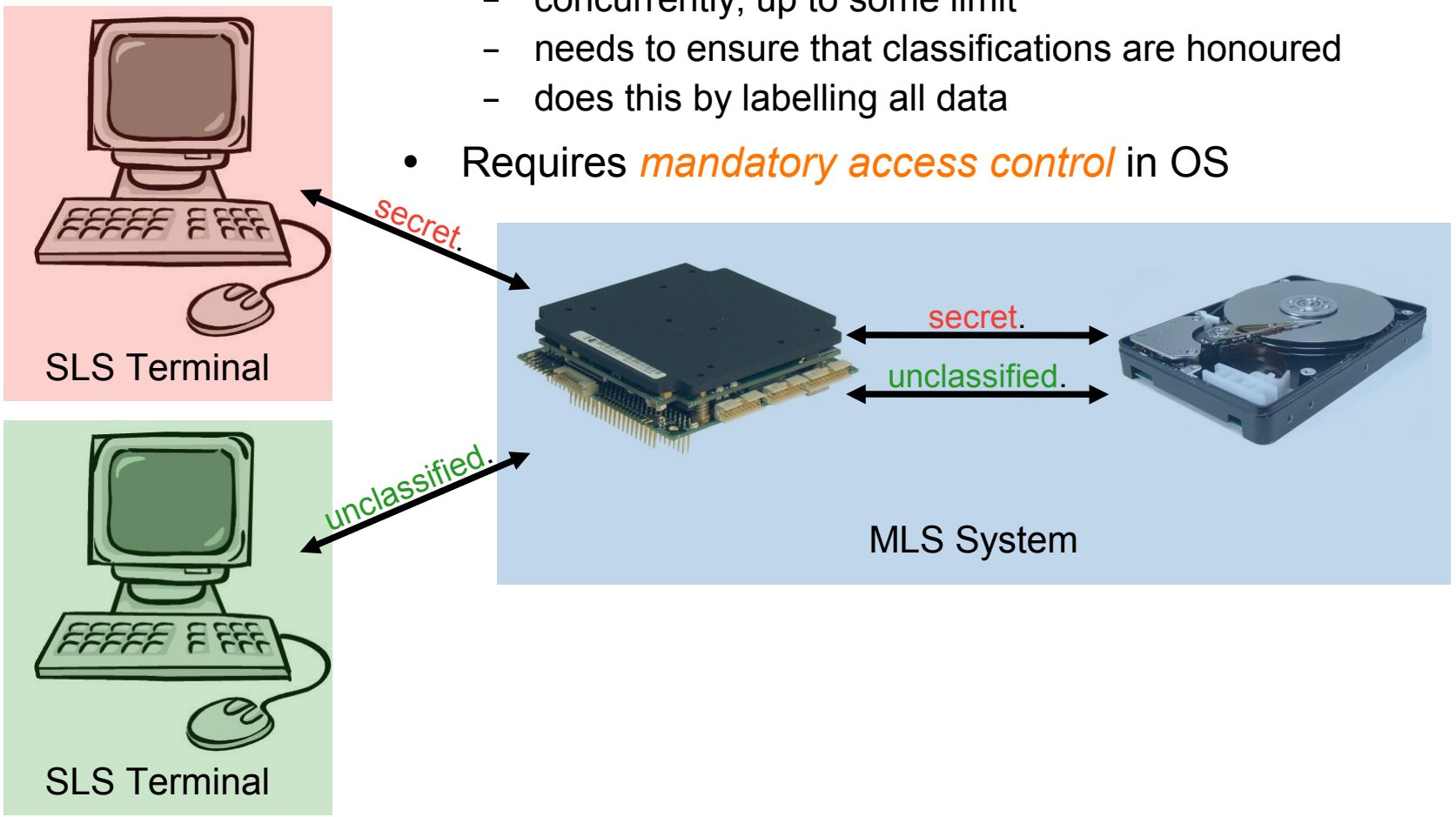
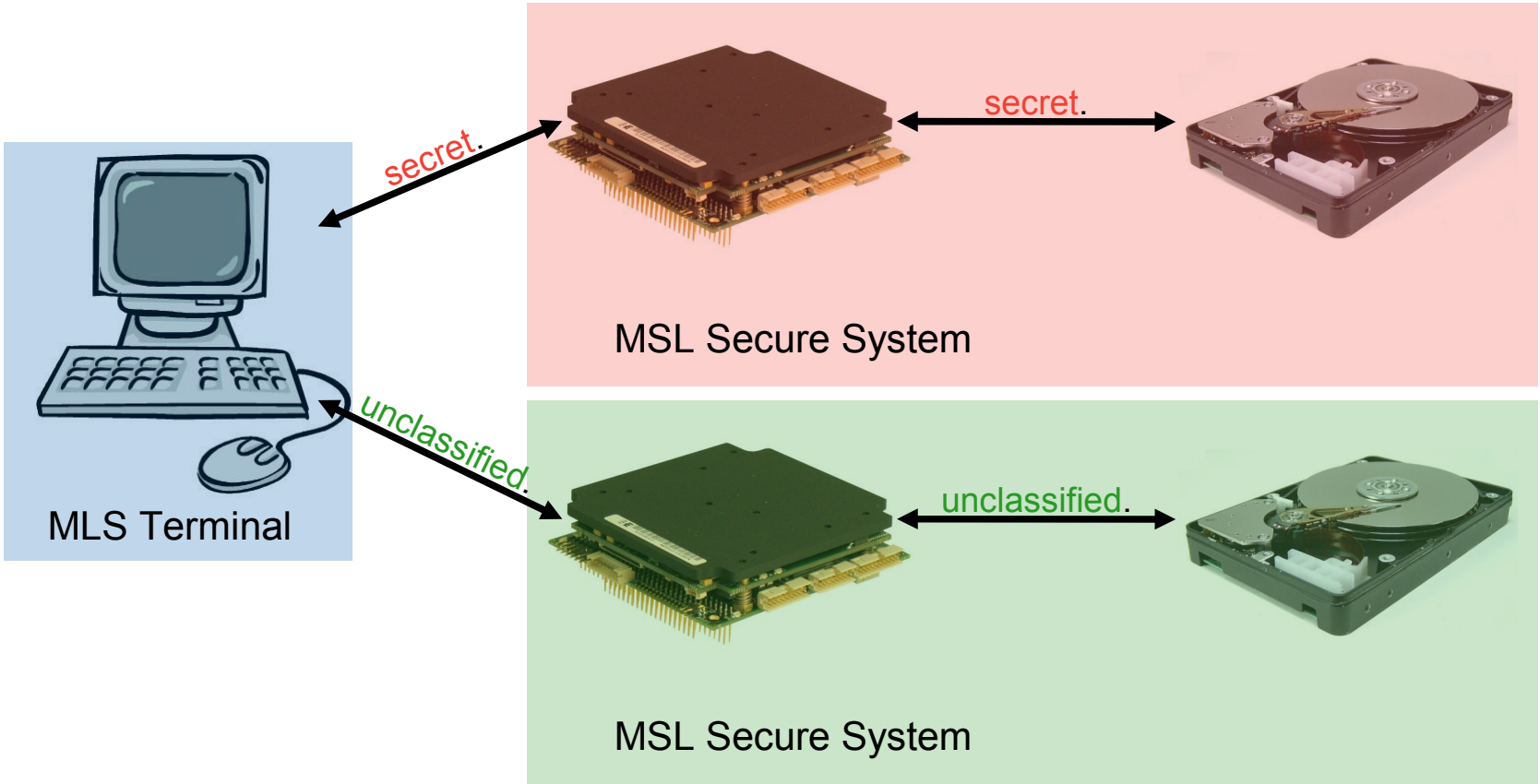
- Suitable for processing data of several security levels
  - concurrently, up to some limit
  - needs to ensure that classifications are honoured
  - does this by labelling all data
- Requires *mandatory access control* in OS



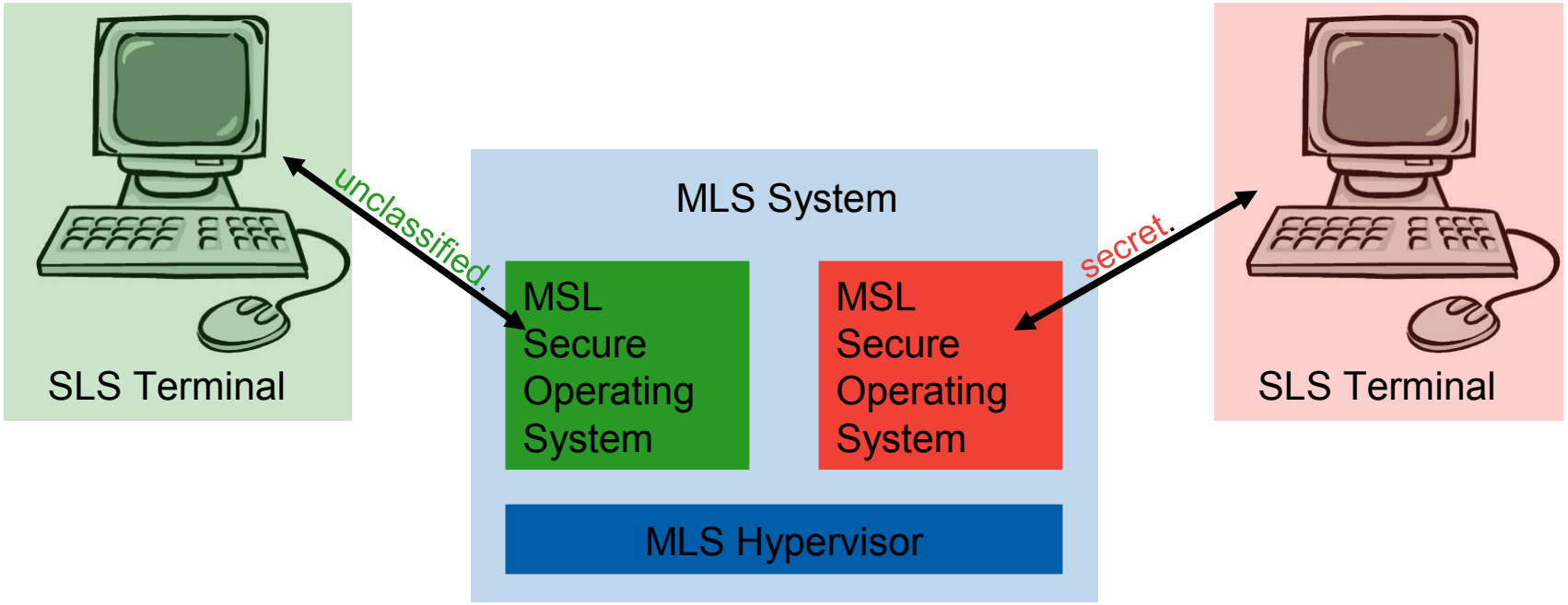
MLS + MSL System

- MLS component handles multiple levels of data
- Only a single level of data goes to each of the MSL secure systems



MLS System Using Virtualization

- MLS hypervisor runs several MSL secure OSes in individual virtual machines
- Result is MLS system
- An example of a *multiple independent levels of security* (MILS) architecture
  - Hypervisor here operates as a *separation kernel*
  - Separates (isolates) different *security domains*



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Security Policies: Categories

- *Discretionary* (user-controlled) policies (DAC)
  - e.g A can read B's objects only with A's permission
  - User decides about access (at their discretion)
  - Classical example: Unix permissions
- *Mandatory* (system-controlled) policies (MAC)
  - e.g certain users cannot ever access certain objects
  - No user can change these
  - Focus on restricting *information flow*
  - Inherent requirement for MLS systems, MILS
- *Role-based* policies (RBAC)
  - Agents can take on specific pre-defined roles
    - Well-defined set of roles for each agent
    - e.g normal user, sysadmin, database admin
  - Access rights depend on role

Models for Security Policies

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- Represent a whole class of security policies
- Most system-wide policies focus on confidentiality
  - e.g military-style multi-level security models
- Classical example is *Bell-LaPadula* model [BL76]
  - Example of a *labelled security model*
  - Most others developed from this
  - Orange Book based on this model
- Other models
  - *Chinese-wall* policy focuses on conflict of interest
  - *Clark-Wilson* model focuses on separation of duty

Bell-LaPadula Model

- Each object a has a security *classification* $L(a)$
- Each agent o has a security *clearance* $L(o)$
- Classifications
  - e.g top secret > secret > confidential > unclassified
- Rule 1 (*no read up*):
  - A can *read* o only if $L(a) \geq L(o)$
  - Standard confidentiality
- Rule 2 (✸ *Property — no write down*)
  - A can *write* o only if $L(a) \leq L(o)$
  - Prevents *leakage* (accidental of by conspiracy)

Bell-LaPadula Model

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- Mother of all military-style security models
- Inherently requires implementation as MAC
  - All subjects must be bound to policy
- If implemented inside a single system, requires MLS system
- Major limitation: cannot deal with *declassification*
  - Needed to pass any information from high- to low-security domain
    - Logging
    - Command chain
    - Documents where sensitive portions have been censored
    - Encrypted data
- Typically dealt with by special *privileged functions*
  - Outside security policy
  - Outside systematic reasoning
  - Part of TCB
  - Likely source of security holes

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Security Mechanisms

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- Used to implement security policies
- Based on access control
  - Discretionary access control (DAC)
  - Mandatory access control (MAC)
  - Role-based access control (RBAC)
- Access rights
  - *Simple rights*
    - Read, write, execute/invoke, send, receive
  - *Meta rights* (DAC only)
    - Copy
      - Propagate own rights to another agent
    - Own
      - Change rights of an object or agent

Access Control Matrix

	Objects			
Agents	S_1	S_2	O_3	O_4
S_1	terminate	wait, signal, send	read	
S_2	wait, signal, terminate			read, execute, write
S_3		wait, signal, receive		
S_4	control		execute	write

Defines each agent's rights on any object

Note: agents are objects too

Properties of the Access Control Matrix

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- Rows define agents' *protection domains (PDs)*
- *Columns* define objects' *accessibility*
- Dynamic data structure:
  - Frequent permanent changes (e.g. object creation, `chmod`)
  - Frequent temporary changes (e.g. `setuid`)
- Very *sparse* with many repeated entries
- Impractical to store explicitly

Protection-Matrix Implementation: ACLs

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Represent column-wise: access control list (ALC):

- *ACL* associated with *object*
- Usually condensed via *domain classes* (UNIX, NT groups)
- Full ACLs used by Multics, Apollo Domain, Andrew FS, NTFS
- Can have *negative rights* to:
  - Reduce window of vulnerability
  - Simplify exclusion from groups
- Sometimes implicit (Unix process hierarchy)
- Implemented in almost all commercial systems

Protection-Matrix Implementation: Capabilities

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Represent row-wise: capabilities [DV 66]:

- *Capability List* associated with agent
  - Each capability confers a certain right to its holder
- Can have *negative rights* to:
  - Reduce window of vulnerability
  - Simplify management of groups of capabilities
- Caps have been popular in research for a long time
- Few successful commercial systems until recently:
  - main one is IBM System/38 / AS400 / i-Series
  - increasingly appearing in commercial systems (usually add-on)

Capabilities

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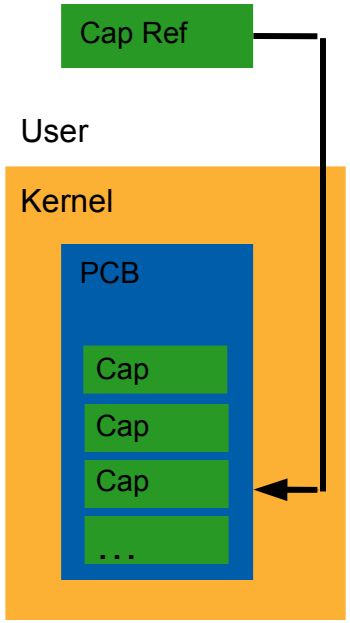
- Main advantage of capabilities is the *fine-grained access control*:
  - Easy to provide specific agents access to individual objects
- Capability presets *prima facie* evidence of the *right to access*
  - Capability ⇒ *object identifier* (implies naming)
  - Capability ⇒ (set of) *access rights*
    - Any representation must contain object ID and access rights
    - Any representation must protect capability from forgery
- How are caps implemented and protected?
  - *Tagged* — protected by hardware
    - Popular in the past, rarely today (exception: IBM i-Series)
  - *Sparse* (or *user-mode*) — protected by sparsity
    - probabilistically secure, like encryption
    - propagation outside system control — hard to enforce security policies
  - *Partitioned*/*segregated* — protected by software (kernel)
    - main version of caps used in modern systems

Segregated Capabilities

- System maintains *capability list* (Clist) with each agent (process)
  - User code uses indirect references to caps (clist index)
    - c.f Unix file descriptors
  - System validates permissions on access
    - syscall or page-fault time
- Many research systems
  - Hydra, Mach, EROS, and many others
- Increasingly commercial systems
  - KeyKOS (92), OKL4 (08)
  - Add-on to Linux, Solaris



Confinement

- Problem 1: Executing untrusted code
  - You downloaded a game from the internet
  - How can you be sure it doesn't steal/corrupts your data?
- Problem 2: Digital rights management (DRM)
  - You own copyrighted material (e.g. entertainment media content)
  - You want to let others use it (for a fee)
  - How can you prevent them from making unauthorised copies?
- You need to *confine* the program (game, viewer) so it cannot leak
- Cannot be done with most protection schemes!
  - Not with Unix or most other ACL-based schemes
  - Not with most tagged or sparse capability schemes
  - Multi-level security has some inherent confinement (but can't do DRM)
- Some protection models can confine in principle
  - e.g segregated caps system, can instruct system not to accept any
  - EROS has formal proof of confinement of a model of the system [SW00]
  - Similar seL4 (machine-checked proof)
- In practice difficult to achieve due to *covert channels*

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Design Principles for Secure OS

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- Least privilege (POLA)
- Economy of mechanisms
- Fail-safe defaults
- Complete mediation
- Open design
- Separation of privilege
- Least common mechanisms
- Psychological acceptability

Least Privilege

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- Also called the *principle of least authority* (POLA)
- Agent should only be given the minimal rights needed for task
  - Minimal protection domain
  - PD determined by *function*, not *identity*
    - Unix *root* is evil
    - Aim of role-based access control (RBAC)
  - Rights added as needed, removed when no longer needed
  - Violated by all mainstream OSes
- Example: executing web applet
  - Should not have all of user's privileges, only minimal access
  - Hard to do with ACL-based systems
  - Main motivation for using caps

Least Privilege: Implications for OS

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- OS kernel executes in privileged mode of hardware
  - Kernel has unlimited privilege!
- POLA implies keeping kernel code to an absolute minimum
  - This means a secure OS must be based on a microkernel!
- Trusted computing base can bypass security
- POLA requires that TCB is minimal
  - Microkernel plus minimal security manager

Economy of Mechanisms

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- KISS principle of engineering
  - “keep it simple, stupid!”
- Less code/features/stuff ⇒ less to get wrong
  - Makes it easier to fix if something does go wrong
  - Complexity is the natural enemy of security
- Also applies to interfaces, interactions, protocols, ...
- Specifically applies to TCB

Fail-Safe Defaults

- Default action is no-access
  - If action fails, system remains secure
  - If security administrator forgets to add rule, system remains secure
  - “better safe than sorry”

Complete Mediation

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- Check every access
  - Violated in Unix file access:
    - Access rights checked at open(), then cached
    - Access remains enabled until `close()`, even if attributes change
  - Also implies that any rights propagation must be controlled
    - Not done with tagged or sparse capability systems
- In practice conflicts with performance!
  - Caching of buffers, file descriptors etc
  - Without caching unacceptable performance
- Should at least limit window of opportunity
  - e.g guarantee caches are flushed after some fixed period
  - Guarantee no cached access after revoking access

Open Design

- Security must not depend on secrecy of design or implementation
  - TCB must be open to scrutiny
  - *Security by obscurity is poor security*
    - Not all security/certification agencies seem to understand this
- Note that this doesn't rule out passwords or secret keys
  - But their creation requires careful *cryptoanalysis*

Separation of Privilege

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- Require a combination of conditions for granting access
  - e.g user is in group wheel *and* knows the root password
  - Take-grant model for capability-based protection:
    - Sender needs *grant* right on capability
    - Receiver needs *take* right to accept capability
  - In reality, the security benefit of a separate *take* right is minimal
    - Practical cap implementations only provide *grant* as a privilege
- Closely related to least privilege

Least Common Mechanisms

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- Avoid sharing mechanisms
  - Shared mechanism ⇒ shared channel
  - Potential covert channel
- Inherent conflict with other design imperatives
  - Simplicity ⇒ shared mechanisms
  - Classical tradeoff...

Psychological Acceptability

- Security mechanisms should not add to difficulty of use
  - Hide complexity introduced by security mechanisms
  - Ensure ease of installation, configurations, use
  - Systems are used by humans!
- Inherently problematic:
  - Security inherently inhibits ease of use
  - Idea is to minimise impact
- Security-usability tradeoff is to a degree unavoidable

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Common-Criteria Protection Profiles

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- Controlled Access Protection Profile (CAPP)
  - standard OS security, derived from Orange Book C2
  - certified up to level EAL3
- Single-level Operating System Protection Profile
  - superset of CAPP
  - certified up to EAL4+
- Labeled Security Protection Profile (LSPP)
  - mandatory access control for COTS OSes
  - similar to Orange Book B1
- Role-based Access Control Protection Profile
- Multi-level Operating System Protection Profile
  - superset of CAPP, LSPP
  - certified up to EAL4+
- Separation Kernel Protection Profile (SKPP)
  - strict partitioning
  - certifications aiming for EAL6–7

Common Criteria Assurance Levels

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- EAL1: functionally tested
  - simple to do, can be done without help from developer
- EAL2: structurally tested
  - functional and interface spec
  - black- and white-box testing
  - vulnerability analysis
- EAL3: methodically tested and checked
  - improved test coverage
  - procedures to avoid tampering during development
  - highest assurance level achieved for Mac OS X

Common Criteria Assurance Levels

NICTA

- EAL4: methodically designed, tested and reviewed
  - Design docs used for testing, avoid tampering during delivery
  - Independent vulnerability analysis
  - Highest level feasible on existing product (not developed for CC certific.)
  - Achieved by a number of main-stream OSes
    - Windows 2000: EAL4 in 2003
    - SuSe Enterprise Linux: EAL4 in 2005
    - Solaris-10: EAL4+ in 2006
      - Controlled access protection profile (CAPP) — *Note: EAL3 profile!*
      - Role-based access control PP — *example of non-NSA PP?*
    - RedHat Linux EAL4+ in 2007
  - They still get broken!
    - Certification is based on assumptions about environment, etc...
    - Most use is outside those assumptions
      - Certification means nothing in such a case
      - Presumably there were no compromises were assumptions held

Common Criteria Assurance Levels

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- EAL5: semi-formally designed and tested
  - Formal model of TEO security policy
  - Semi-formal model of functional spec & high-level design
  - Semi-formal arguments about correspondence
  - Covert-channel analysis
  - IBM z-Series hypervisor EAL5 in 2003 (partitioning)
  - Attempted by Mandrake for Linux with French Government support
- EAL6: semiformally verified design and tested
  - Semiformal low-level design
  - Structured representation of implementation
  - Modular and layered TOE design
  - Systematic covert-channel identification
  - Green Hills Integrity microkernel presently undergoing EAL6+ certification
    - Separation kernel protection profile

Common Criteria Assurance Levels

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- EAL7: formally verified design and tested
  - Formal functional spec and high-level design
  - Formal and semiformal demonstration of correspondence
    - Between specification and low-level design
  - Simple TOE
  - Complete independent confirmation of developer tests
  - LynuxWorks claims LynxSecure separation kernel EAL7 “certifiable”
    - But not *certified*
  - Green Hills also aiming for EAL7

Note:

- *Even EAL7 relies on testing!*
- EAL7 requires proof of correspondence between formal descriptions
- However, no requirement of formalising LLD, implementation
- Hence no requirement for formal proof of implementation correctness

Common Criteria Limitations

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- Little (if any) use in commercial space outside national security
  - This was one of the intentions, by all indications, CC failed here
- Very expensive
  - Industry rule-of-thumb: EAL6+ costs $10k per LOC
  - Dominated by documentation requirements
  - No “credit” for doing things better
    - Eg formal methods instead of excessive documentation
- Lower EALs of limited practical use
  - Windows is EAL4+ certified!
  - Marketing seems to be main driver behind EAL3–4 certification
- Over-evaluation abuses system
  - Eg.CAPP (EAL3 profile) certification to EAL4
  - In reality a pointless exercise

Formal Verification

- Based on mathematical model of the system
- Complete verification requires two parts:
  - Proof that model satisfies requirements of security policies
    - Typically prove generic properties that actual policies map to
    - Required by CC EAL5–7
  - Proof that implementation has same properties as model
    - Proof of correspondence between model and implementation
    - Not required by CC even at EAL7
    - Done by some kernels with very limited functionality
    - Never done for any general-purpose OS!
- Model-checking (static analysis) is *incomplete* formal verification
  - Shows presence or absence of certain properties
    - e.g uninitialised variables, array-bounds overflows
  - Nevertheless useful for assurance

Common Criteria and Formal Verification

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EAL	Requirem.	Funct Spec	HLD	LLD	Implem.
EAL 1	Informal	Informal	Informal	Informal	Informal
EAL 2	Informal	Informal	Informal	Informal	Informal
EAL 3	Informal	Informal	Informal	Informal	Informal
EAL 4	Informal	Informal	Informal	Informal	Informal
EAL 5	Formal	Semiformal	Semiformal	Informal	Informal
EAL 6	Formal	Semiformal	Semiformal	Semiformal	Informal
EAL 7	Formal	Formal	Formal	Semiformal	Informal

Trusted Computing vs Secure OS

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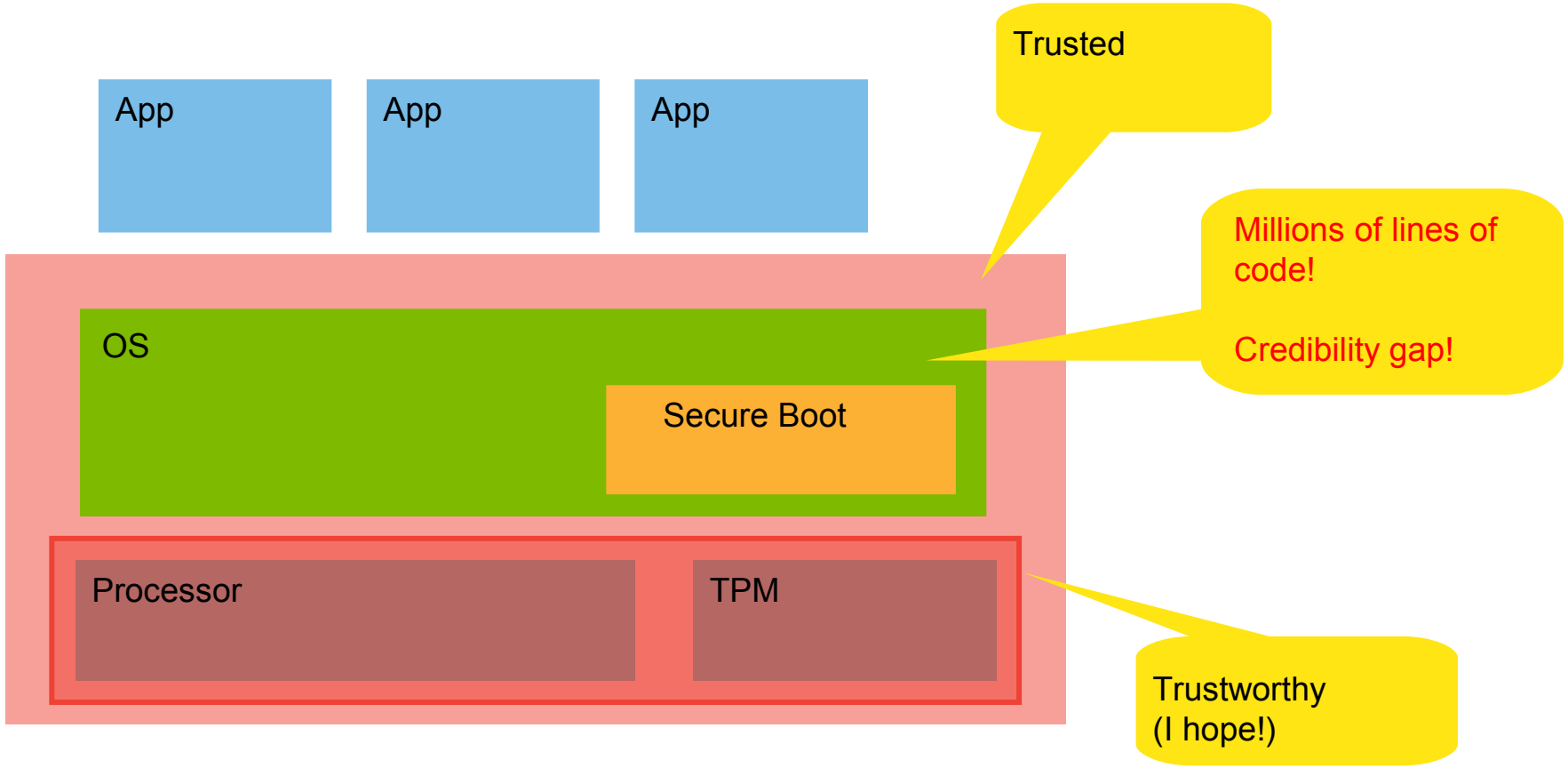
- TPM-based trusted-computing approach is based on
  - Hardware root of trust
  - Mechanisms to provide a chain of trust
- Objective is to guarantee that system boots into a well-defined configuration
  - Guarantees that a particular OS binary is running
  - What does this mean about security/trustworthiness?

Trusted Computing vs Secure OS



→ TPM-based trusted-computing approach is of limited use

- As long as the OS isn't trustworthy

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OS Design for Security

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- Minimize kernel code
  - Kernel = code that executes in privileged mode
  - Kernel can bypass any security
  - Kernel is inherently part of TCB
  - Kernel can only be verified as a whole (not in components)
    - It's hard enough to verify a minimal kernel
- How?
  - Generic mechanisms (economy of mechanisms)
  - No policies, only mechanisms
  - Mechanisms as simple as possible
  - Only code that must be privileged in order to support secure systems
  - Free of covert channels:
    - No global names, absolute time
- Formally specify API

OS Design for Security

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- Minimize mandatory TCB
  - Unless formally verified, TCB must be assumed imperfect
  - The smaller, the fewer defects
  - POLA requires, economy of mechanisms leads to minimal TCB
- Ensure TCB is well defined and understood
  - Make security policy explicit
  - Make granting of authority explicit
- Flexibility to support various uses
  - Make authority delegatable
  - Ensure mechanisms allow high-performance implementation
- Design for verifiability
  - Minimize implementation complexity

Example: NICTA's seL4

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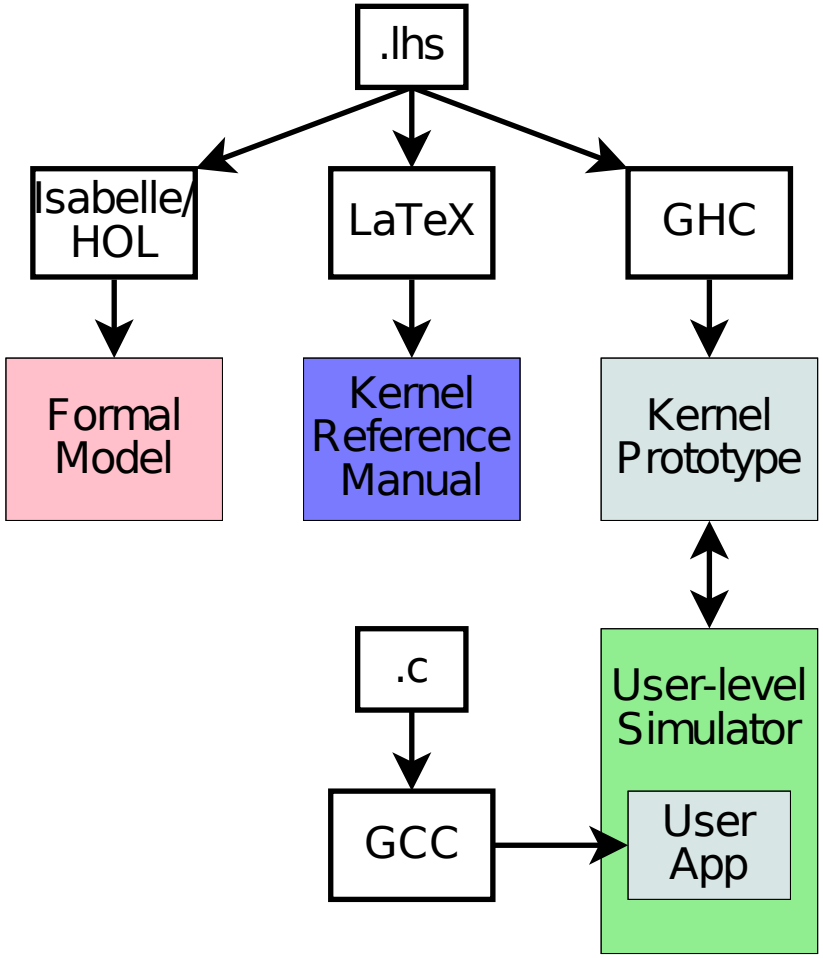
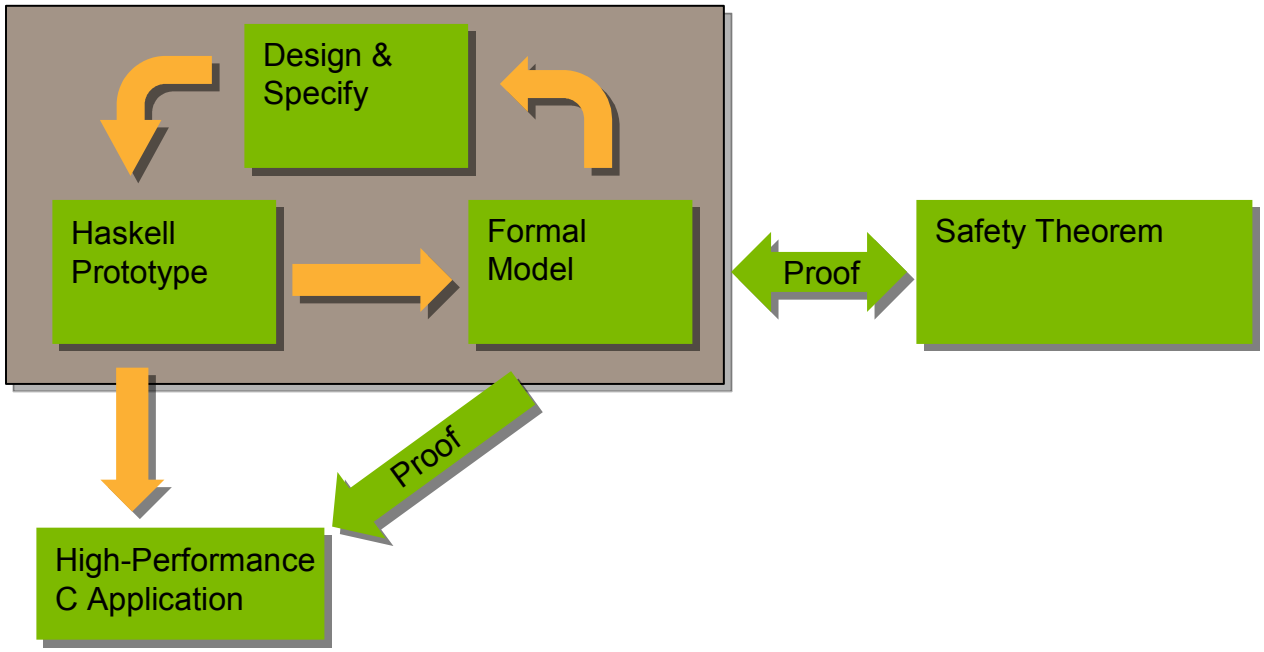
- High-security version of L4 microkernel API
  - All authority granted by capabilities
  - Only four system calls: read, write, create, derive
  - Kernel memory explicitly managed by user-level resource manager
  - 7,000–10,000 lines of kernel code
- Semi-formal API spec in Haskell
  - Easily formalised in theorem prover
  - Machine-checked proofs of security properties
  - Designed for formal verification, to be finished mid-2008

Kernel Prototyping in Haskell

- Model the kernel in detail
- Literate Haskell to model
  - Pure functional programming language
  - Embedded documentation
  - Close to Isabelle/HOL
  - Formalized Haskell becomes intermediate representation for refinement proof
- Executable
  - Supports running user-level code

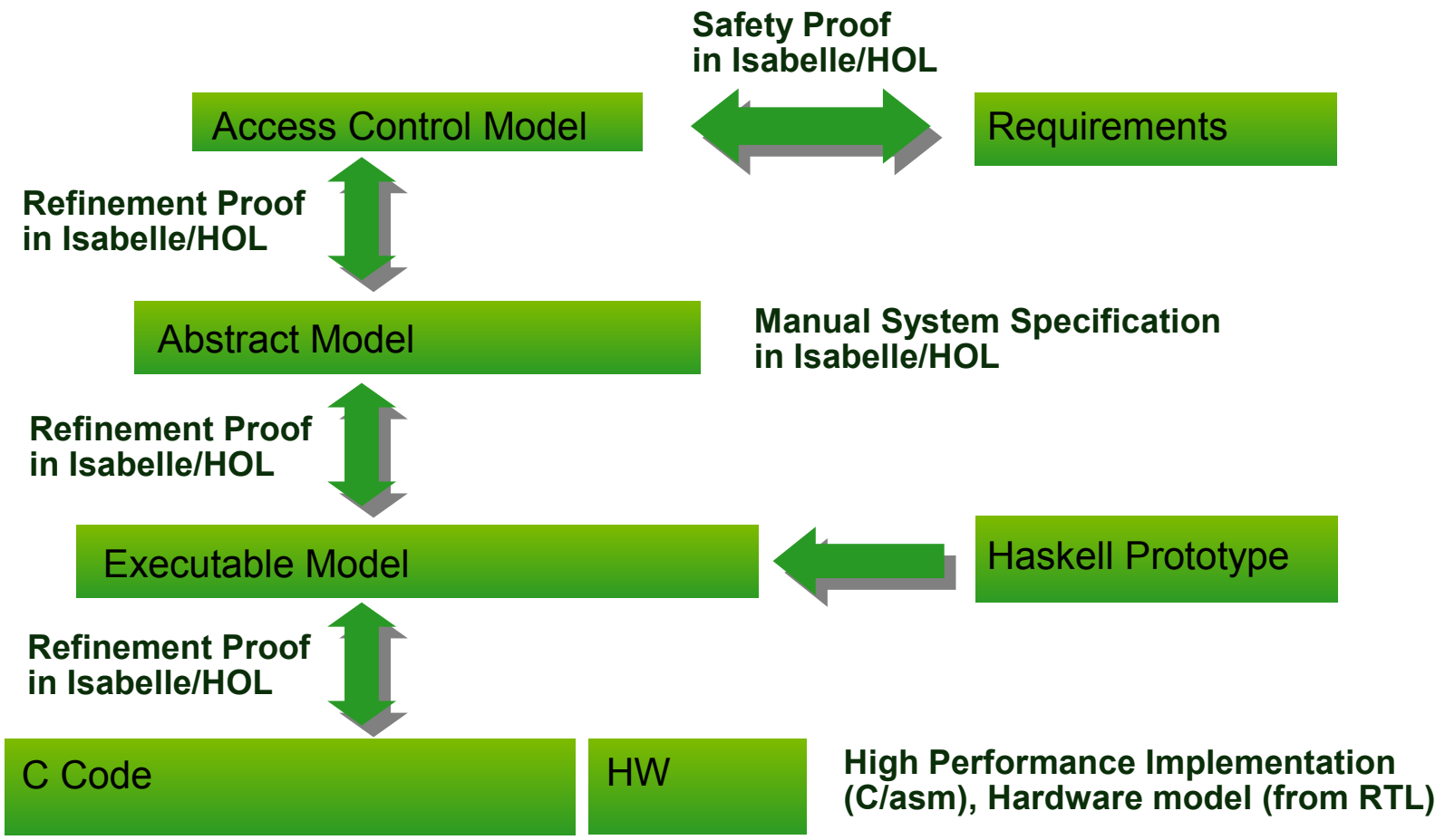


Iterative Design and Formalisation



- Haskell kernel executes native binaries on simulator
- Exposes usability issues early
- Tight formal design integration

seL4 Correctness Proof



seL4 Formal Verification

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Aim: Complete proof chain from security requirements to implementation

- Running since January 2004
- Achieved to date:
  - Formal, machine-checked proofs of safety properties (isolation)
  - Formal, machine-checked proof of concrete spec satisfying the abstract spec
    - In CC language: formally-verified high-level design
  - Formal, machine-checked proof that executable model refines spec
    - In CC language: formally-verified low-level design
  - Already most formally-analysed general-purpose OS ever
- In progress:
  - Formal, machine-checked proof that implementation refines spec
    - In CC language: formally-verified implementation
  - To be completed by December 2008
- *You want trusted virtualization — you've got it!*

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From **imagination** to **impact**