School of Computer Science & Engineering

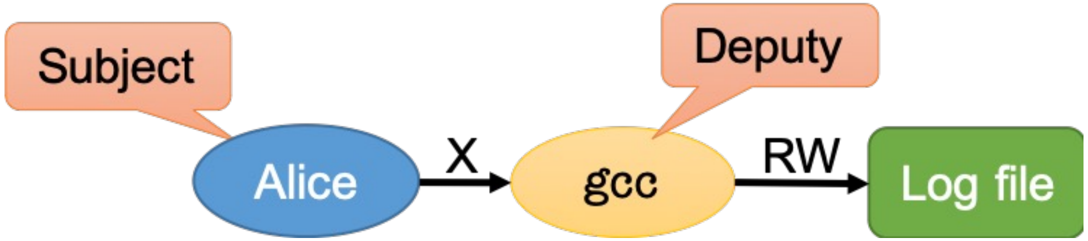
COMP9242 Advanced Operating Systems

2023 T3 Week 05 Part 2

Security Fundamentals

@GernotHeiser

Incorporating material from Toby Murray



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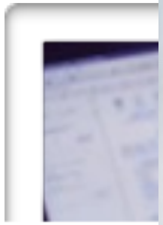
What is Security?

Different things to different people:



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On June 8, as the investigation into the initial intrusion p
response team shared with relevant agencies that there was a high degree of confidence that OPM systems containing information related to the background investigations of current, former, and prospective Federal government employees, and those for whom a Federal background investigation was conducted, may have been compromised.

Sharing is Caring

Computer Security

Protecting *my interests* (that are under computer control) from *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 insufficient for protecting TOP SECRET (TS) classified data on an Internet-connected machine

Security claims only make sense

- wrt *defined objectives*
- while *identifying threats*
- and *identifying secure states*

State of OS Security

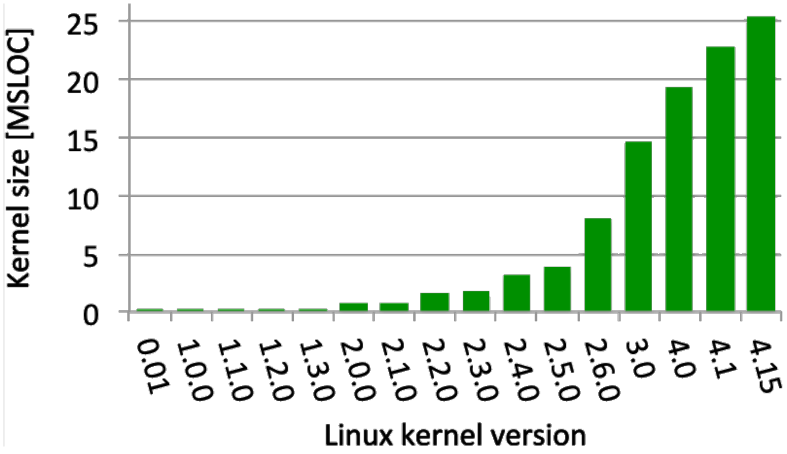
- Traditionally:
  - Has not kept pace with evolving user demographics
    - Focused on e.g. Defence and Enterprise
  - Has not kept pace with evolving threats
    - Much security work is reactive rather than proactive

Some things are getting better:

- more systematic hardening of OSes
- Better security models in smartphones compared to desktops

Other things are getting worse:

- OS kernel sizes keep growing
- Fast growth in attacker capabilities
- Slow growth in defensive capabilities



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)
  - Principle of “do not pay for what you don’t need”

Good mechanisms lend themselves to correct implementation and *verification*!

Security Design Principles

Saltzer & Schroeder [SOSP ’73, CACM ’74]

- **Economy of mechanism** – KISS
- **Fail-safe defaults** – as in any good engineering
- **Complete mediation** – check everything
- **Open design** – no security by obscurity
- **Separation of privilege** – defence in depth
- **Least privilege** – aka *principle of least authority* (POLA)
- **Least common mechanism** – minimise sharing
- **Psychological acceptability** – if it’s hard to use it won’t be

Common OS Security Mechanisms

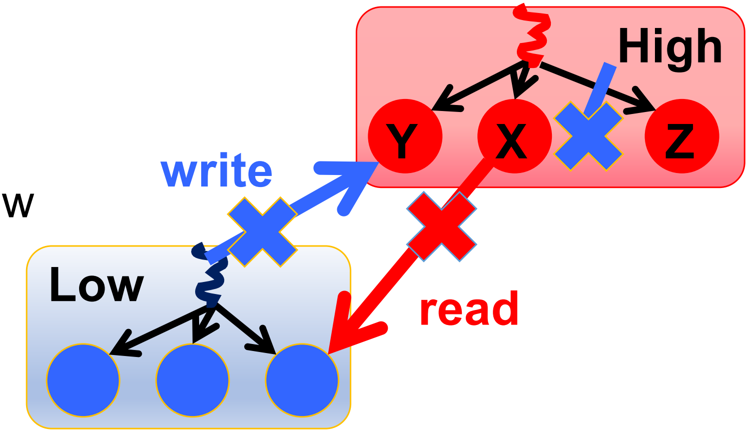
- Access Control Systems
  - control what each process can access

Fundamental mechanism

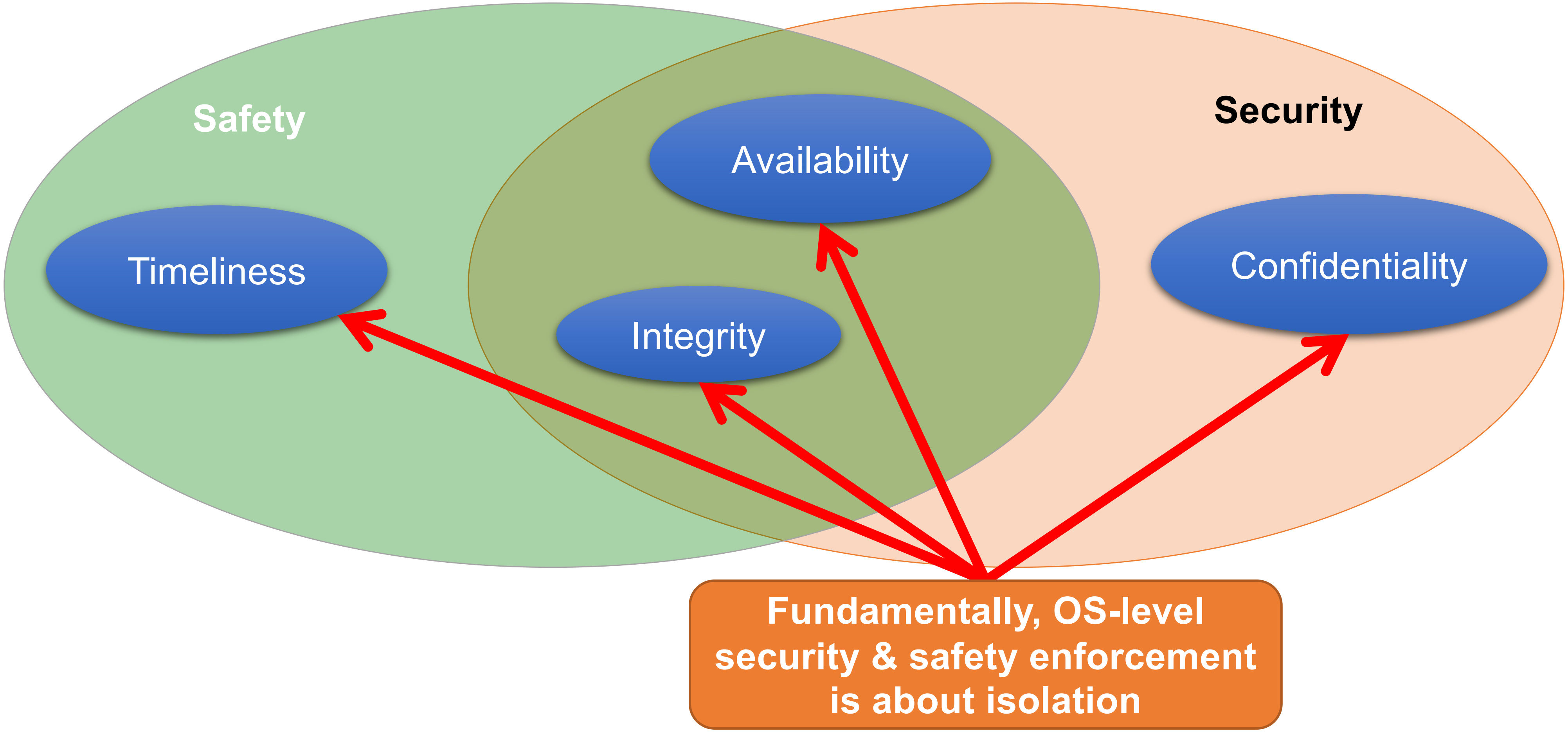
- Authentication Systems
  - confirm the identity on whose behalf a process is running
- Logging
  - for audit, detection, forensics and recovery
- Filesystem Encryption
- Credential Management
- Automatic Updates

Security Policies

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



Security vs Safety



Fundamentally, OS-level security & safety enforcement is about isolation

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
  - some *trusted* entities behave as expected
- Problem: implicit or poorly understood assumption

Good assumptions are

- *clearly identified*
- *verifiable*!

Trust

- Systems always have **trusted** entites
  - whose misbehaviour can cause insecurity
  - hardware, OS, sysadmin ...

Trusted computing base (TCB):
The set of all trusted entities

- Secure systems require the TCB to be **trustworthy**
  - achieved through **assurance** and **verification**
  - shows that the TCB is unlikely to misbehave

Minimising the TCB is key for ensuring correct behaviour

Assurance and Formal Verification

- **Assurance**:
  - systematic evaluation and testing
  - essentially an intensive and onerous form of quality assurance
- **Formal verification**:
  - mathematical proof
- **Certification**: independent examination
  - confirming that the assurance or verification was done right

Assurance and formal verification aim to establish correctness of
- mechanism design
- mechanism implementation

Covert Channels

- Information flow not controlled by security mechanisms
  - Confidentiality requires absence of all such channels
- **Storage** Channel: Attribute of shared resource used as channel
  - Controllable by access control
- **Timing** Channel: Temporal order of shared resource accesses
  - Outside of access-control system
  - Much more difficult to control and analyse
- Other **physical** channels:
  - Power draw
  - Temperature (fan speed)
  - Electromagnetic emanation
  - Acoustic emanation

```
void leak(secret){
  if (secret) {
     create (“/tmp/true”);
  } else {
     create (“/tmp/false”);
  }
}
```

Covert Timing Channels

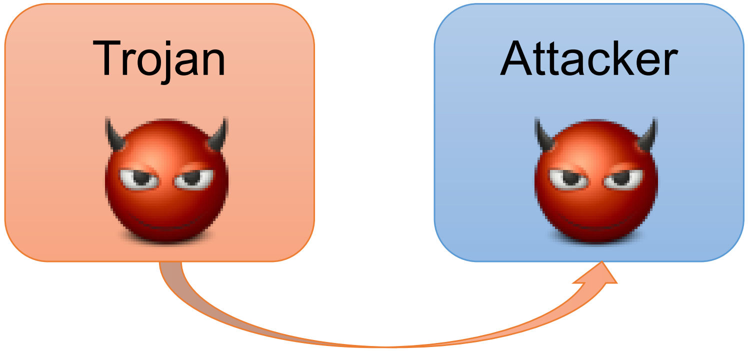
- Created by shared resource whose effect on timing can be monitored
  - network bandwidth, CPU load, memory latency ...
- Requires access to a time source
  - Anything that allows processes to synchronise
  - Generally any relative occurrence of two event
- Critical issue is channel bandwidth
  - low bandwidth limits damage
    - why DRM ignores low bandwidth channels

Typical timing channels:
- Measure server response times
- Measure own progress

Beware of amplification!
- eg leaking passwords

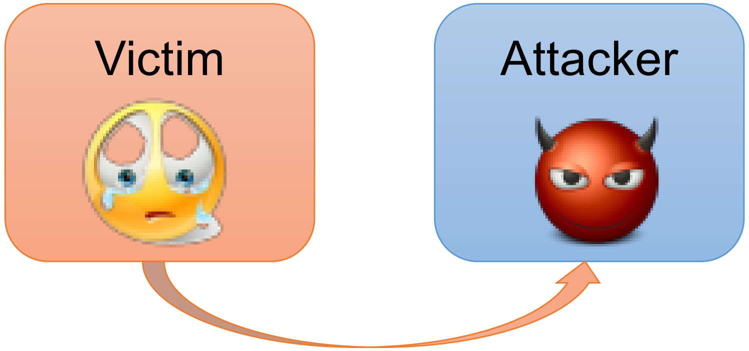
Covert Channels vs Side Channels

Covert Channel



- Trojan intentionally creates signal through targeted resource use
- Worst-case bandwidth

Side Channel



- Attacker uses signal created by victim’s innocent operations
- Much lower bandwidth

Summary of Introduction

- Security is very subjective, needs well-defined objectives
- 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

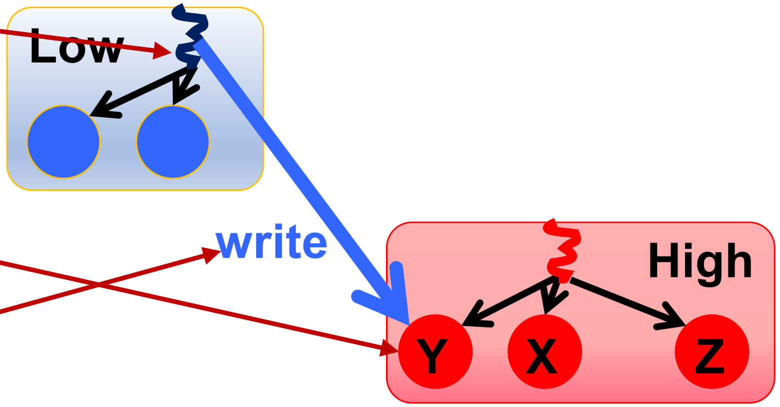
The OS is necessarily part of the TCB

Access-Control Principles

Access Control

Who can access **what** in which **ways**

- The “who” are called **subjects** (or **agents**)
  - 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



Access Control Mechanisms & Policies

- Access Control **Policy**
  - Specifies allowed accesses
  - And how these can change over time
- Access Control **Mechanism**
  - Used to implement the policy
- Certain mechanisms lend themselves to certain kinds of policies
- Some policies cannot be expressed using your OS's mechanisms

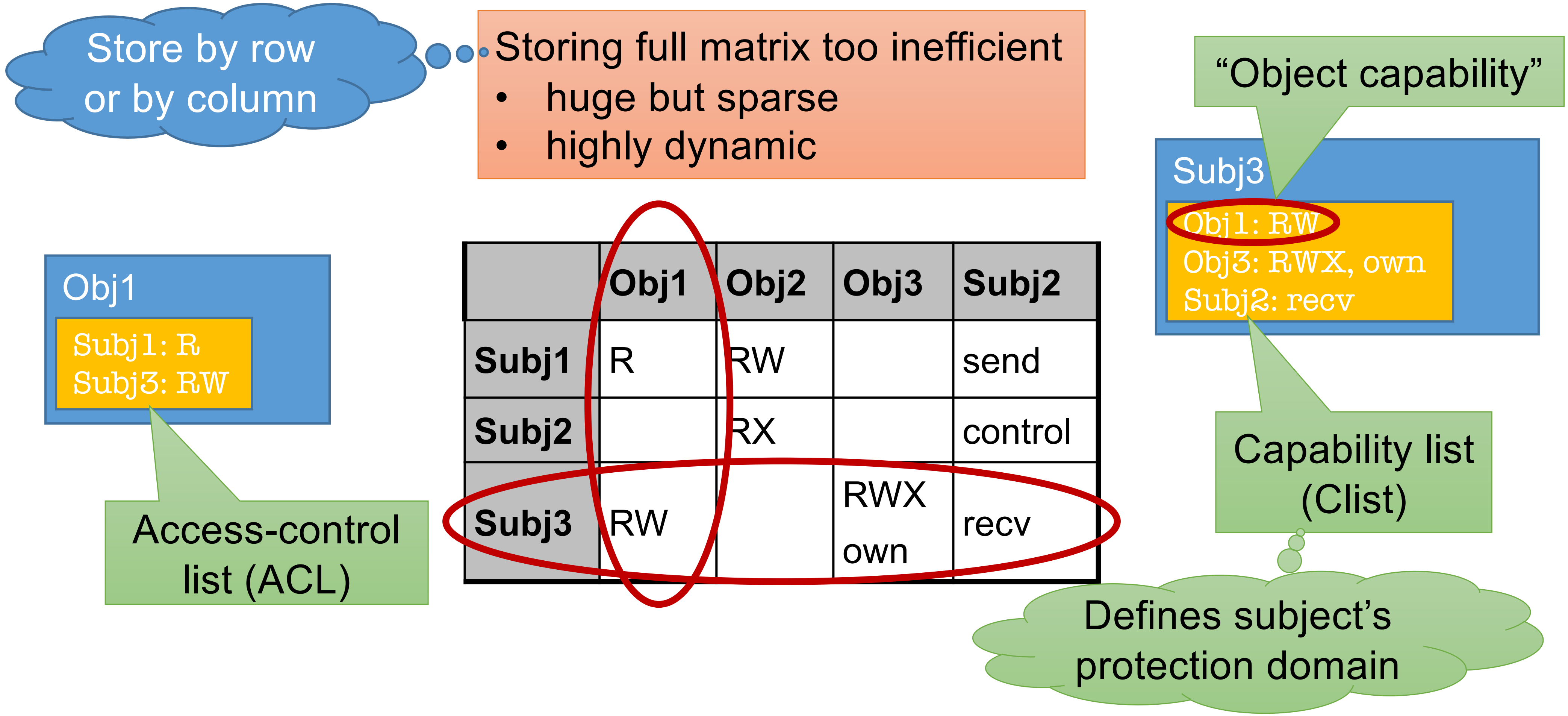
Protection State: Access-Control Matrix

Defines system's protection state at a particular time instance [Lampson '71]

Subjects are also objects

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

Representing Protection State



Store by row or by column

Storing full matrix too inefficient

- huge but sparse
- highly dynamic

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

Obj1

```
Subj1: R
Subj3: RW
```

Access-control list (ACL)

Subj3

```
Obj1: RW
Obj3: RWX, own
Subj2: recv
```

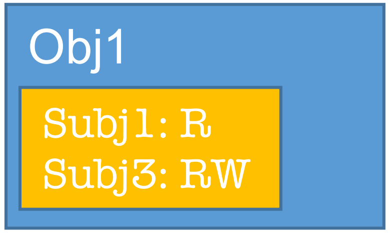
“Object capability”

Capability list (Clist)

Defines subject’s protection domain

Access Control Lists (ACLs)

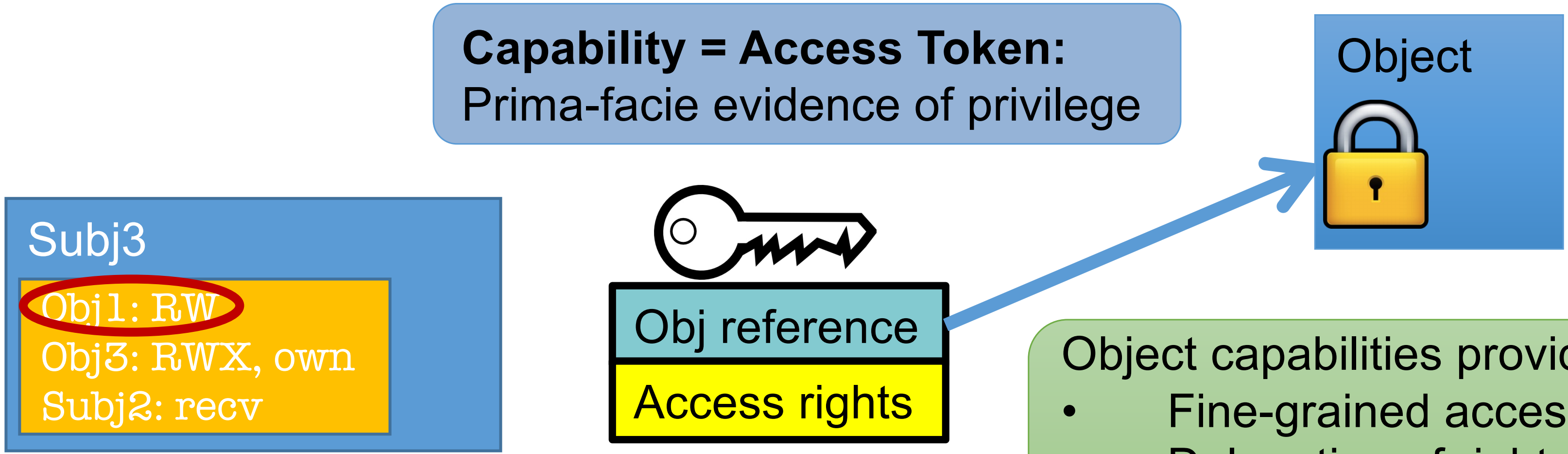
- Subjects usually aggregated into classes
  - e.g. UNIX: owner, group, everyone
  - more general lists in Windows, recent Linux
  - Can have negative rights
    eg. to overwrite group rights
- Meta-permissions (e.g. own)
  - control class membership
  - allow modifying the ACL



Used by all mainstream OSes

Capability-Based Access Control

Capability = Access Token:
Prima-facie evidence of privilege



Object capabilities provide:

- Fine-grained access control
- Delegation of rights
- Reasoning about information flow

Linux “capabilities” do not have these properties!

Any system call is invoking a capability:

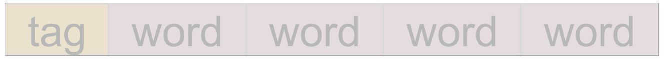
err = cap.method(args);

Used in very few commercial systems:

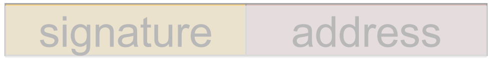
- IBM System/38→AS/400→i-Series
- KeyKOS [Bomberger et al, 1992]
- L4 microkernels, Google Fuchsia

Capabilities: Implementations

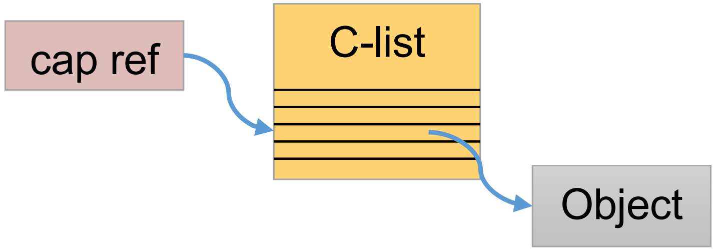
- Capabilities must be unforgeable
  - Traditionally protected by hardware (tagged memory), eg System-38
  - Can be copied etc like data
  - eg IBM System/38, Hydra, CHERI



- On conventional hardware, either:
  - Stored as ordinary user-level data, but unguessable due to sparseness
    - contains password or secure hash: PCS [Anderson'86], Mungi [Heiser'98]
    - **"sparse" capabilies**



  - Privileged kernel data
    - referred to by user programs by index/address
    - eg Mach [Accetta'86], EROS [Shapiro'99], seL4, Unix file descriptors
    - **"partitioned" or "segregated" capabilities**



ACLs & Capabilities – Duals?

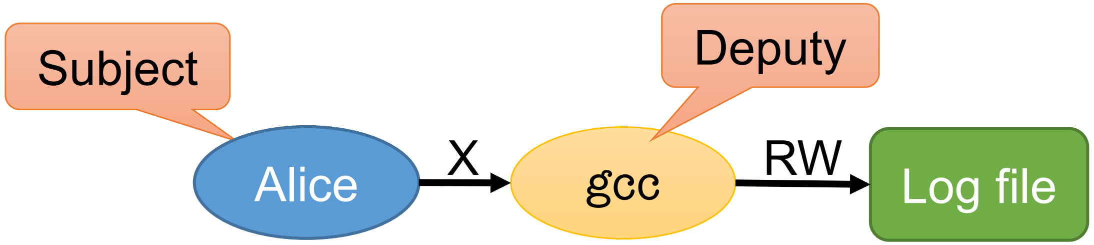
- In theory dual representations of access control matrix
- Practical differences:
  - Naming and namespaces
    - Ambient authority
    - Deputies
  - Evolution of protection state
  - Forking
  - Auditing of protection state

Duals: Naming and Name Spaces

- ACLs:
  - objects referenced by **name**
    - requires separate (global) name space
    - e.g. open(“/etc/passwd”,O_RDONLY)
  - require a subject (class) namespace
    - e.g. UNIX users and groups
- Capabilities:
  - objects referenced by **capability**
  - no further namespace required
  - cannot even *name* object without access

Covert storage channel?

Duals: Confused Deputy



```
alice$ gcc –o LogFile source.c
```

- ACLs separate naming and permissions
- Deputy depends on *ambient authority*
  - Uses own authority for access

Confused-deputy problem is unsolvable with ACLs!

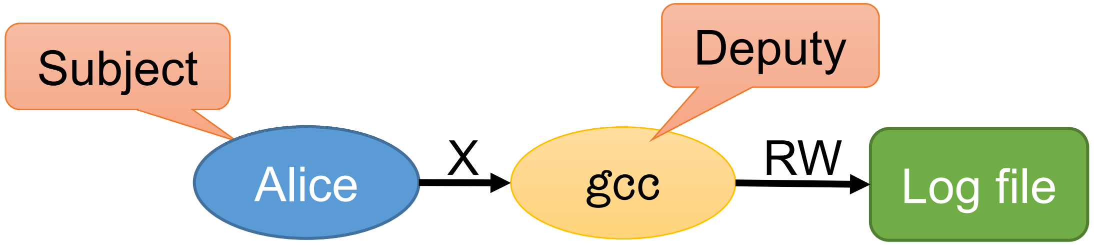
Unix:

- Log file is group admin
- Alice not member of admin
- gcc is set-UID admin

```
static char* log = “/var/gcc/log”;
int gcc (char *src, *dest) {
   int s = open (src, RDONLY );
   int l  = open (log, APPEND);
   int d = open (dest, WRONLY);
    …
   write (dest, …);
}
```

Clobber log!

Duals: Confused Deputy



```
alice$ gcc –o LogFile source.c
```

- Caps are both names and permissions
- Presentation is *explicit*, not ambient
- Can't name something if don't have access!

Capabilities avoid confused deputies

Cap system:

- gcc holds w cap for log file
- Alice holds r cap for source, w cap for destination
- Alice holds no cap for log file

```
static cap_t log = <cap>;
int gcc (cap_t src, dest) {
   fd_t s = open (src, RDONLY );
   fd_t l = open (log, APPEND);
   df_t d = open (dest, WRONLY);
   …
   write (d, …);
}
```

Open fails!

Linux "capabilities" do not help!

Duals: Evolution of Protection State

ACLs: Protection state changes by modifying ACLs

- Requires certain meta-permissions on the ACL

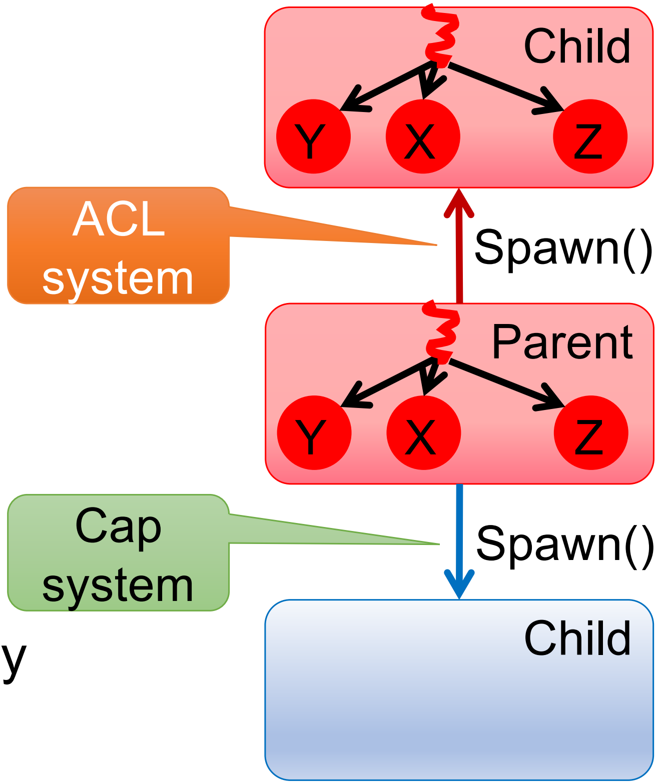
Capabilities: Protection state changes by delegating and revoking caps

- Fundamental properties enable reasoning about *information flow*:
  - A can send message to B only if A holds cap to B
  - A can obtain access to C only if it receives message with cap to C
- *Right to delegate* may also be controlled by capabilities, e.g.:
  - A can delegate to B only if A has a *delegatable* capability to B
  - A can delegate X to B only if it has *grant* authority on X

seL4: Grant right on endpoint

Duals: Process Creation

- 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
  - Opposite of least privilege!
- Capabilities: child has no caps by default
  - Parent gets a capability to the child upon fork
  - Used to delegate explicitly the necessary authority
  - **Defaults to least privilege**



Duals: Auditing of Protection State

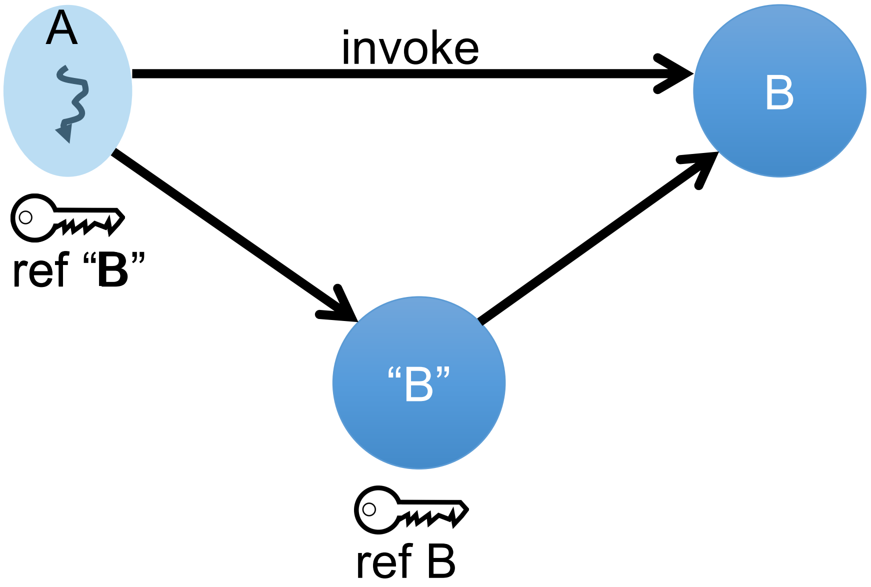
- Who has permission to access a particular object (right now)?
  - ACLs: Just look at the ACL
  - Caps: hard to determine with sparse or tagged caps, or for partitioned
- What objects can a particular subject access (right now)?
  - Capabilities: Just look at its capabilities
  - ACLs: may be impossible to determine without full scan

"Who can access my stuff?"
vs
"How much damage can C do?"

Interposing Access

Caps are opaque object references (pure names)

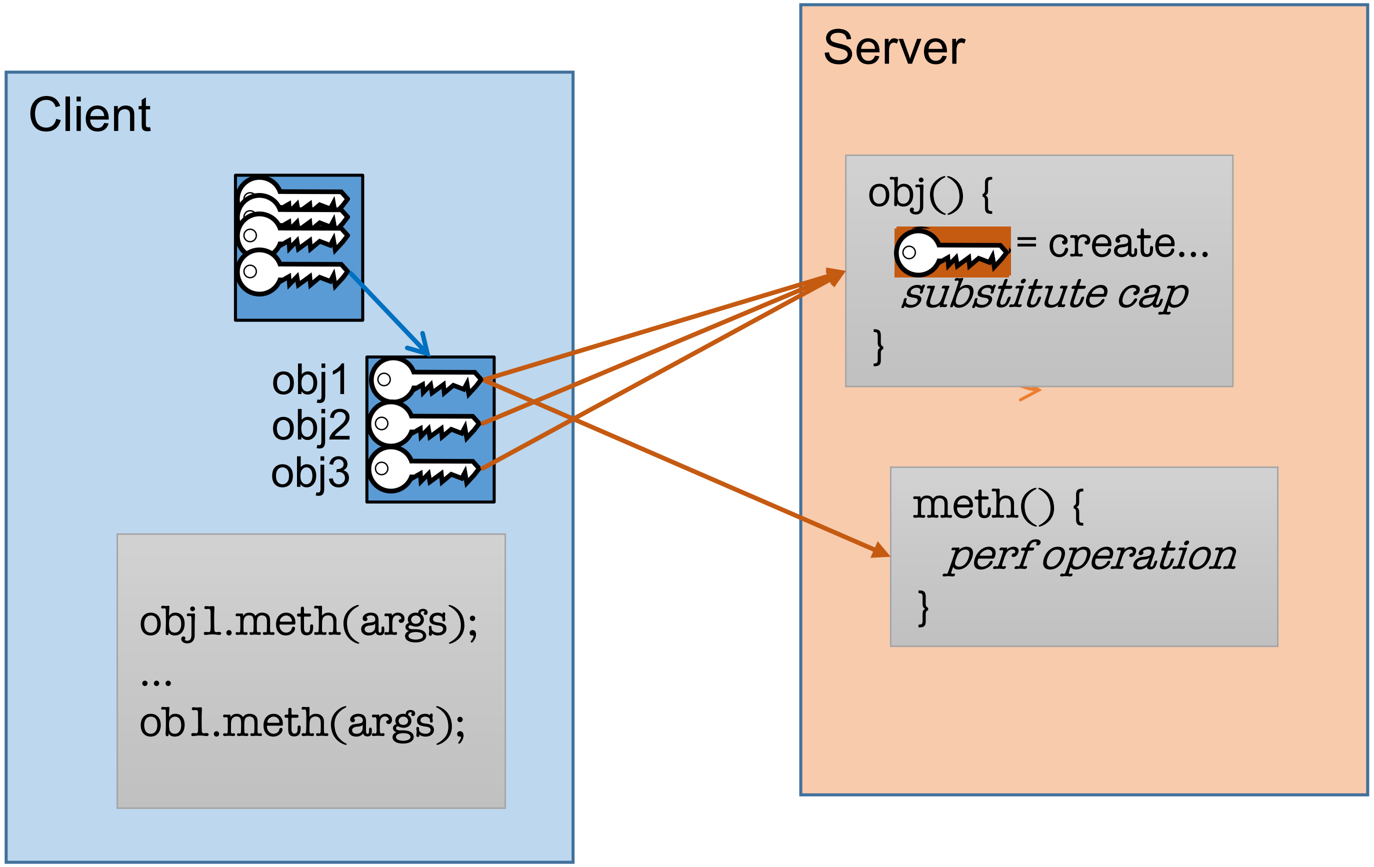
- Holder cannot tell which object a cap references nor the authority
- Supports transparent interposition (virtualisation)



Usage:

- API virtualisation
- Reference (security) monitor
  - Security policy enforcement
  - Info flow tracing
  - Packet filtering…
- Secure logging
- Debugging
- Lazy object creation

Example: Lazy Object Construction



```
obj() {
   = create...
  substitute cap
}
```

```
meth() {
  perf operation
}
```

```
obj1.meth(args);
...
ob1.meth(args);
```

Duals: Satzer & Schroeder Principles

Security Principle	ACLs	Capabilities
Economy of Mechanism	Dubious	Yes!
Fail-safe defaults	Generally not	Yes!
Complete mediation	Yes (if properly done)	Yes (if properly done)
Open design	Neutral	Neutral
Separation of privilege	No	Doable
Least privilege	No	Yes
Least common mechanism	No	Yes, but…
Psychological acceptability	Neutral	Neutral

Mandatory vs Discretionary Access Control

Discretionary Access Control (DAC):

- Users can make access control decisions
  - Delegate their access to other users etc.

Can I stop my browser leaking secrets?

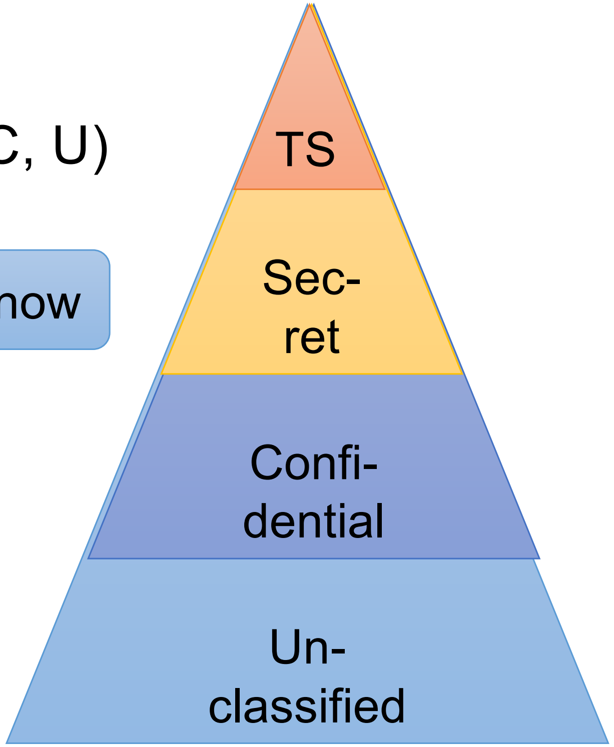
Mandatory Access Control (MAC):

- System enforces administrator-defined policy
- Users can only make access control decisions subject to mandatory policy
- Can prevent untrusted applications from causing damage
- Traditionally used in national security environments

MAC: Bell & LaPadula (BLP) Model [1966]

- MAC Policy/Mechanism
  - Formalises national security classifications
- Every object assigned a **classification** (eg TS, S, C, U)
  - orthogonal security **compartments**
- Classifications ordered in a **lattice**
  - e.g. TS > S > C > U
- Every subject assigned a **clearance**
  - Highest classification they're allowed to learn

Need-to-know



Labelled security:

- Subjects and objects are *labelled*
- Permitted accesses: relation over labels
  `allow(subject.label, object.label, operation)`

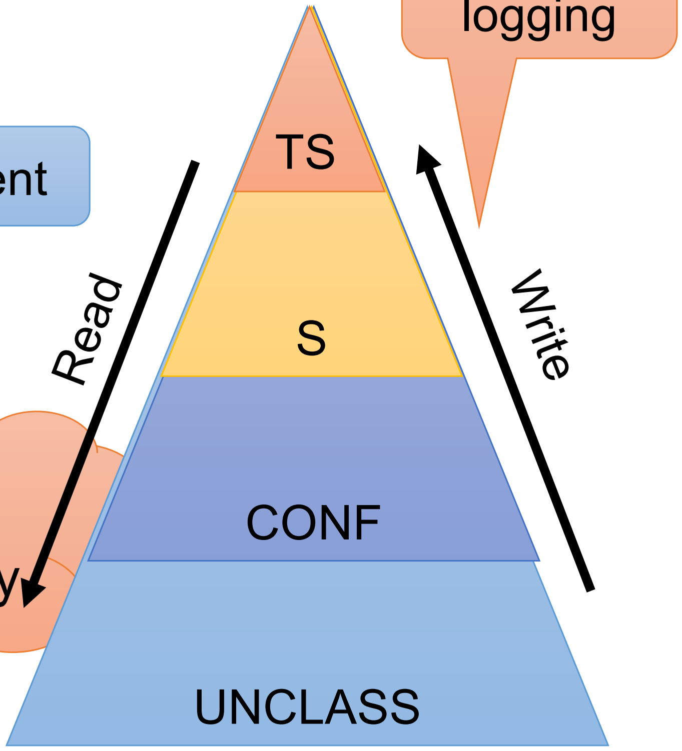
BLP: Rules

- **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
- In practice need exceptions
  - allow *trusted* entity to write down
  - *"de-classify"*

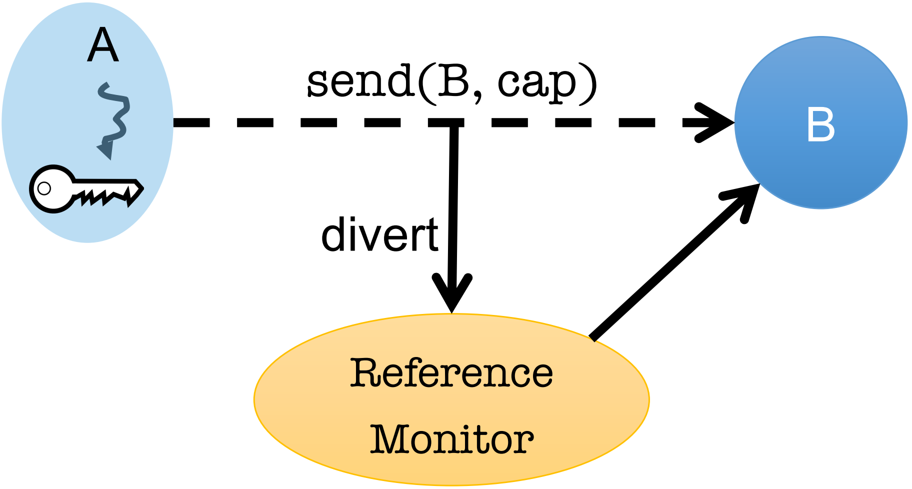
Confinement

Trend to over-classify

E.g. logging



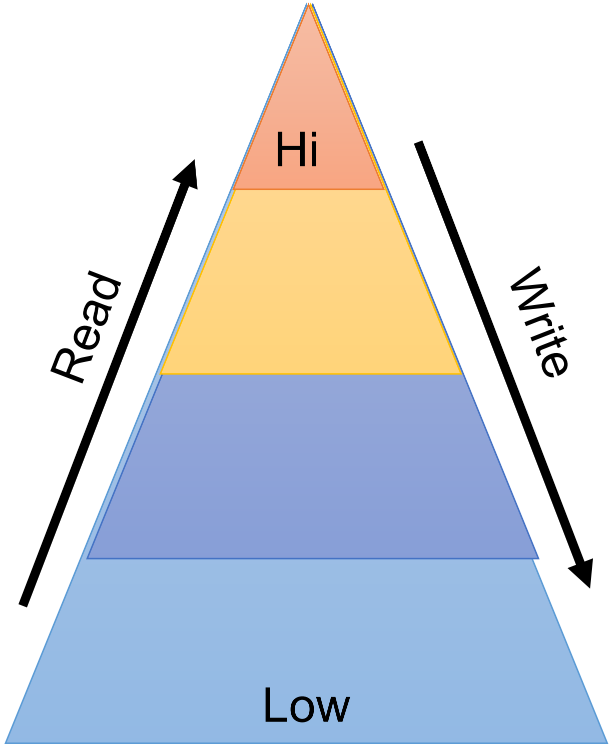
MAC With Caps: Reference Monitor



```
interpose_transfer(cap) {
  if (A.clear > B.clear) {
    c = mint(cap, -r);
    send(B,c);
  } else if (A.clear < B.clear) {
    c = mint(cap, -w);
    send(B,c);
  } else {
    send(B,cap);
  }
}
```

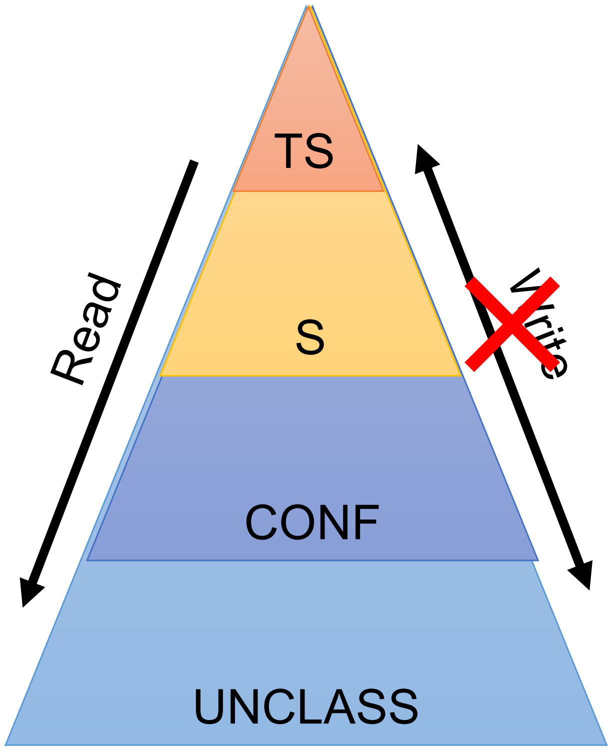
MAC: Biba Integrity Model

- 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)`



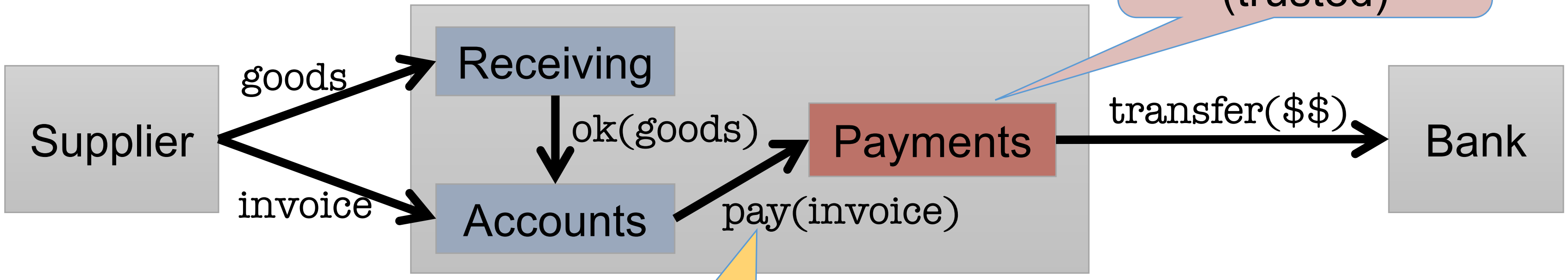
Confidentiality + Integrity

- BLP+Biba allows no information flow across classes
- Practicality requires weakening
  - Assume high-classified subject to treat low-integrity info responsibly
  - Allow read-down
- **Strong *-Property** (“matching writes only”):
  - **s** can write **o** iff `clearance(s) = class(o)`
  - Eg for logging, high reads low data and logs



Clark & Wilson Model

- In commercial settings integrity is more important than confidentiality
- Restrict possible operations to *well-formed transactions*
  - eg payment issued only after goods and invoice received

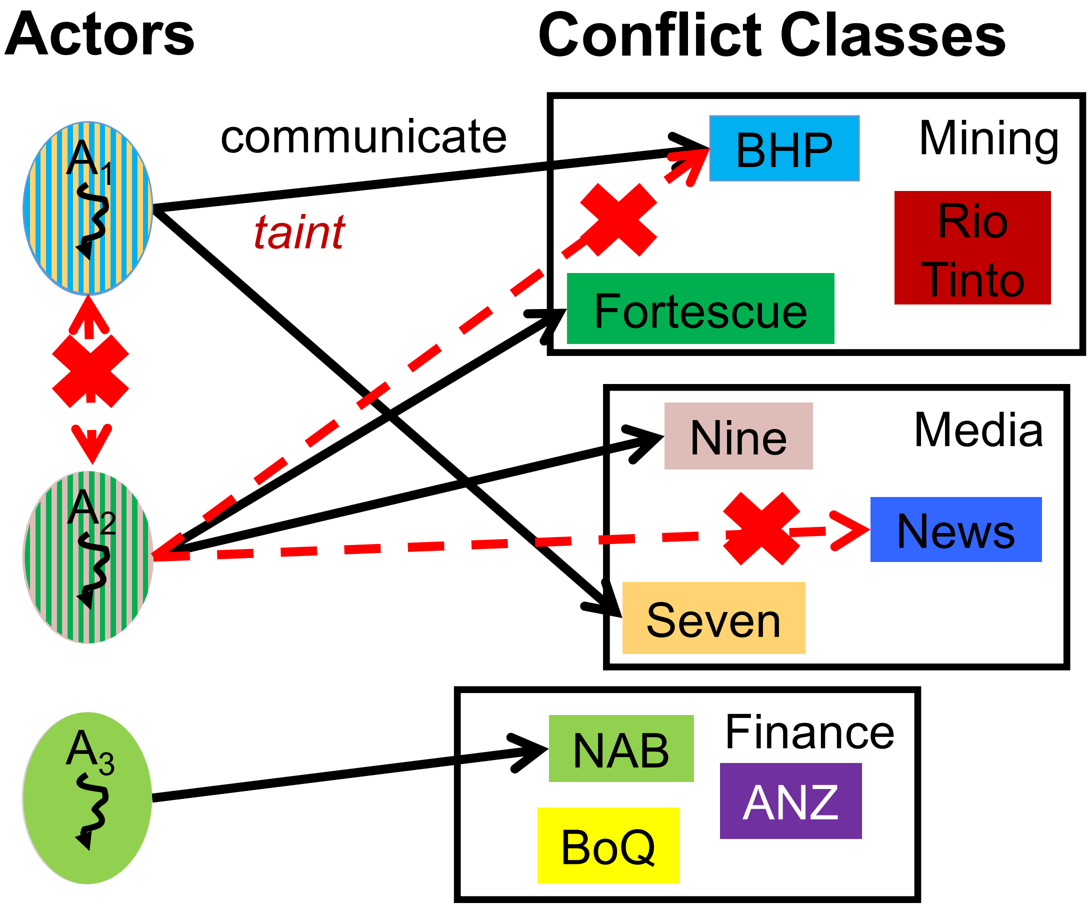


Integrity-critical (trusted)

Rights amplification

- Easy with caps
- SetUID cesspit with ACLs

Chinese Wall (aka Brewer & Nash) Model



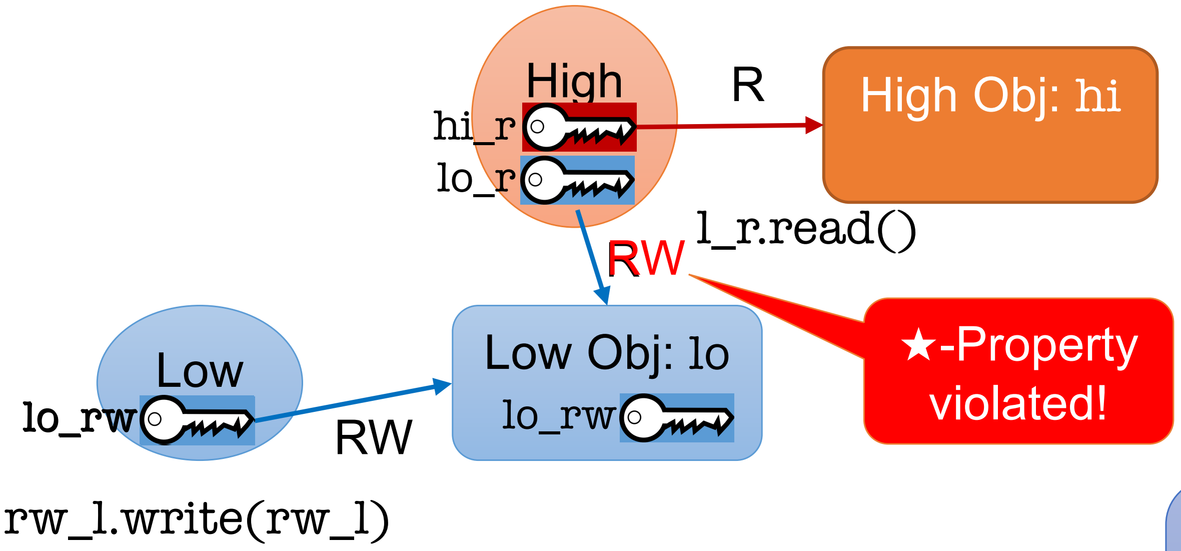
Communication *taints* actor:

- tainted actor cannot communicate with other entity in same conflict class

Conflict-of-interest prevention

- Law practices
- Consultancies

Boebert’s Attack on Capability Machines



High

hi_r

lo_r

R

High Obj: hi

l_r.read()

RW

Low

lo_rw

RW

Low Obj: lo

lo_rw

★-Property violated!

rw_l.write(rw_l)

Takeaway: Need mechanism to limit cap propagation: *take-grant model*

“On the inability of an unmodified capability machine to enforce the ★-property” [Boebert’84]

Works where caps are indistinguishable from data (HW & sparse caps)

Decidability

Safety: Given initial *safe state s*, system will never reach *unsafe state s'*

Decidability: AC system is decidable if safety can aways be computationally determined

Equivalent to halting problem [Harrison, Ruzzo, Ullman '75]

- Most capability systems are decidable
- Unclear for many common ACL systems

Summary: AC Principles

- ACLs and Capabilities:
  - Capabilities tend to better support least privilege
  - But ACLs can be better for auditing
- MAC good for global security requirements
- Not all mechanisms can enforce all policies
  - e.g. ★-property with sparse or HW capabilities
- AC systems should be decidable so we can reason about security