Security Properties

Summer School on Software Security
June 2004

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Outline

- What is computer security?
  - Protecting against worms and viruses?
  - Making sure programs obey their specifications?
  - Still plenty of security problems even if these problems are solved…

Acknowledgments: Steve Zdancewic, Fred Schneider

What is security?

- Security: prevent bad things from happening
  - Confidential information leaked
  - Important information damaged
  - Critical services unavailable
  - Clients not paying for services
  - Money stolen
  - Improper access to physical resources
  - System used to violate law
  - Loss of *value*

… or at least make them less likely

- Versus an adversary!

Attack Sampler #1: Morris Worm

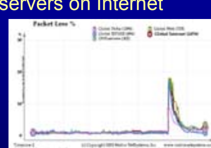
1988: Penetrated an estimated 5 to 10 percent of the 6,000 machines on the internet.

Used a number of clever methods to gain access to a host.
- brute force password guessing
- bug in default sendmail configuration
- X windows vulnerabilities, rlogin, etc.
- buffer overrun in fingerd

Remarks:
- System diversity helped to limit the spread.
- "root kits" for cracking modern systems are easily available and largely use the same techniques.

2002: MS-SQL Slammer worm

- Jan. 25, 2002: SQL and MSDE servers on Internet turned into worm broadcasters
  - YABO
  - Spread to most vulnerable servers on the Internet in less than 10 min!



- Denial of Service attack
  - Affected databases unavailable
  - Full-bandwidth network load ⇒ widespread service outage
  - "Worst attack ever" – brought down many sites, not Internet
- Can't rely on patching!
  - Infected SQL servers at Microsoft itself
  - Owners of most MSDE systems didn't know they were running it…support for extensibility

Attack sampler #2: Love Bug, Melissa

- 1999: Two email-based viruses that exploited:
  - a common mail client (MS Outlook)
  - trusting (i.e., uneducated) users
  - VB scripting extensions within messages to:
    - look up addresses in the contacts database
    - send a copy of the message to those contacts
- Melissa: hit an estimated 1.2 million machines.
- Love Bug: caused estimated $10B in damage.
- Remarks:
  - no passwords, crypto, or native code involved

Attack sampler #3: Hotmail

- 1999: All Hotmail email accounts fully accessible by anyone, without a password
- Just change username in an access URL (no programming required!)
- Selected other Hotmail headlines (1998 99)
  - Hotmail bug allows password theft
  - Hotmail bug pops up with JavaScript code
  - Malicious hacker steals Hotmail passwords
  - New security glitch for Hotmail
  - Hotmail bug fix not a cure-all

Attack sampler #4: Yorktown

- 1998: “Smart Ship” USS Yorktown suffers propulsion system failure, is towed into Norfolk Naval Base
- Cause: computer operator accidentally types a zero, causing divide by zero error that overflows database and crashes all consoles
- Problem fixed two days later

Attack sampler #5: insiders

- Average cost of an outsider penetration is $56,000; average insider attack cost a company $2.7 million (Computer Security Institute/FBI)
- 63 percent of the companies surveyed reported insider misuse of their organization's computer systems. (WarRoom Research)
- Some attacks:
  - Backdoors
  - “Logic bombs”
  - Holding data hostage with encryption
  - Reprogramming cash flows
- Attacks may use legitimately held privileges!
- Many attacks (90%?) go unreported

Terminology

- Vulnerability
  - Weakness that can be exploited in a system
- Attack
  - Method for exploiting vulnerability
- Threat / Threat model
  - The power of the attacker (characterizes possible attacks)
    - E.g., attacker can act as an ordinary user, read any data on disk, and monitor all network traffic.
- Trusted Computing Base
  - Set of system components that are depended on for security
    - Usually includes hardware, OS, some software, …

Who are the attackers?

- Operator/user blunders.
- Hackers driven by intellectual challenge (or boredom).
- Insiders: employees or customers seeking revenge or gain
- Criminals seeking financial gain.
- Organized crime seeking gain or hiding criminal activities.
- Organized terrorist groups or nation states trying to influence national policy.
- Foreign agents seeking information for economic, political, or military purposes.
- Tactical countermeasures intended to disrupt military capability.
- Large organized terrorist groups or nation-states intent on overthrowing the US government.

What are the vulnerabilities?

- Poorly chosen passwords
- Software bugs
  - unchecked array access (buffer overflow attacks)
- Automatically running active content: macros, scripts, Java programs
- Open ports: telnet, mail
- Incorrect configuration
  - file permissions
  - administrative privileges
- Untrained users/system administrators
- Trap doors (intentional security holes)
- Unencrypted communication
- Limited Resources (i.e. TCP connections)

What are the attacks?

- Password Crackers
- Viruses:
  - ILoveYou (VBscript virus), Melissa (Word macro virus)
- Worms
  - Code Red: Port 80 (HTTP), Buffer overflow in IIS (Internet/Indexing Service)
- Trojan Horses
- Root kits, Back Orifice, SATAN
- Social Engineering:
  - "Hi, this is Joe from systems, I need your password to do an upgrade"
- Packet sniffers: Ethereal
- Denial of service: TCP SYN packet floods

Social engineering attacks

E-mail this to a friend   Printable version

Passwords revealed by sweet deal

More than 70% of people would reveal their computer password in exchange for a bar of chocolate, a survey has found.

It also showed that 34% of respondents volunteered their password when asked without even needing to be bribed.

Security crumbles in the face of sweet bribes

A second survey found that 79% of people unwittingly gave away information that could be used to steal their identity when questioned.

Security firms predict that the lax security practices will fuel a British boom in online identity theft.

Security vs. fault tolerance

- Attacks vs. faults
- Reliability community often assumes benign, random faults
  - Failstop failures = system halts
  - Byzantine failure = system behaves arbitrarily badly (under control of adversary)
- Attackers go for the weakest link!
  - It doesn't help to have a $1000 lock on your door if the window is open.

Assumptions and abstraction

- Arguments for security always rest on assumptions:
  - "the attacker does not have physical access to the hardware"
  - "the code of the program cannot be modified during execution"
- Assumptions are vulnerabilities
  - Sometimes known, sometimes not
- Assumptions arise from **abstraction**
  - security analysis only tractable on a simplification (abstraction) of actual system
  - Abstraction hides details (assumption: unimportant)

Risk management

- Cost benefit: high security may be more expensive than benefits obtained
  - Security measures interfere with intended use

security ⟷ functionality / efficiency / cost

- Preventing problems may be infeasible, unnecessary; deterrence may be sufficient
  - Remove the incentive to attack
  - Make it easier to attack someone else
  - Make it too costly to attack

When to enforce security

Possible times to respond to security violations:

- Before execution:
  - analyze, reject, rewrite
- During execution:
  - monitor, log, halt, change
- After execution:
  - roll back, restore, audit, sue, call police

Policy vs. mechanism

- What is being protected (and from what) vs.
- How it is being protected
  (access control, cryptography, …)

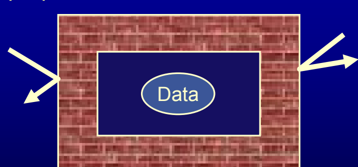
- Want:
  – To know what we need to be protected from
  – Mechanisms that can implement many policies

What is being protected?

- Something with value
- Information with (usually indirect) impact on real world
- Different kinds of protection are needed for different information : ensure different **security properties**
  – **Confidentiality**
  – **Integrity**
  – **Availability**

Properties: Integrity

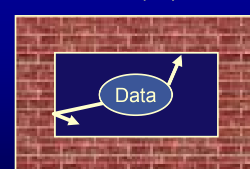
- No improper modification of data



- E.g., account balance is updated only by authorized transactions, only you can change your password
- Integrity of security mechanisms is crucial
- Enforcement: access control, digital signatures,…

Properties: Confidentiality

- Protect information from improper release



- Limit knowledge of data or actions
- E.g. D-Day attack date, contract bids
- Also: secrecy
- Enforcement: access control, encryption,…
- Hard to enforce after the fact…

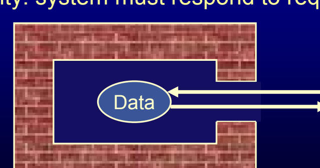
Properties: Privacy, anonymity

- Related to confidentiality
- Privacy: prevent misuse of personal information
- Anonymity: prevent connection from being made between identity of actor and actions
  – Keep identity secret
  – Keep actions secret

Properties: Availability

- Easy way to ensure confidentiality, integrity: unplug computer

- Availability: system must respond to requests



Properties: Nonrepudiation

- Ability to convince a third party that an event occurred (e.g., sales receipt)
- Needed for external enforcement mechanisms (e.g., police)
- Related to integrity

Is security just correctness?

- "System is secure" ≠ "System obeys specification"
- Specifications usually focus on functionality, not security
- Classic specification languages (e.g. Hoare logic) don't talk about security properties
- Security is not preserved under refinement

`public` $\in \mathbb{Z}$	looks secure
`public := secret`	isn't

Safety properties

- "Nothing bad ever happens" (at a particular moment in time)
- A property that can be enforced using only history of program
- Amenable to purely run-time enforcement
- Examples:
  - access control (e.g. checking file permissions on file open)
  - memory safety (process does not read/write outside its own memory space)
  - type safety (data accessed in accordance with type)

Liveness properties

- "Something good eventually happens"
- Example: availability
  - "The email server will always respond to mail requests in less than one second"
- Violated by denial of service attacks
- Can't enforce purely at run time – stopping the program violates the property!
- Tactic: restrict to a safety property
  - "web server will respond to page requests in less than 10 sec or report that it is overloaded."

Security Property Landscape

"System does exactly what it should--and no more"

Privacy

Digital rights

Noninterference (confidentiality, integrity)

Mandatory access control

Discretionary access control

Reference confinement

Type safety

Memory safety

Memory protection

Safety properties

Byzantine Fault Tolerance

Fault Tolerance

Availability

Liveness properties

Security Mechanisms

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Topics

- Fundamental enforcement mechanisms
- Design principles for secure systems
- Operating system security mechanisms

Mechanisms: Authentication

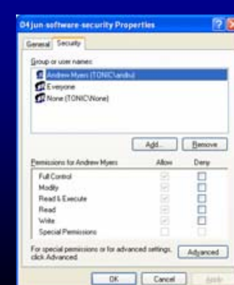
- If system attempts to perform action X, should it be allowed? (e.g., read a file)
  - authentication + authorization
- **Authentication:** what principal p is system acting on behalf of? Is this an authentic request from p?
  - Passwords, biometrics, certificates…

Principals

- A principal is an identity; an abstraction of privileges
  - Process uid
  - E.g., a user (Bob), a group of users (Model airplane club), a role (Bob acting as president)

Mechanisms: Authorization

- **Authorization:** is principal p authorized to perform action A?
- Access control mediates actions by principals
- Example: file permissions (ACLs)



Mechanisms: Auditing

- For after-the-fact enforcement, need to know what happened: auditing
- Audit log records security-relevant actions (who, what, when)
- Authorization + Authentication + Audit = "The gold (Au) standard" : classic systems security
- A fourth kind of mechanism: program analysis and verification
  - Needed for extensible systems and strong security properties… more later

Principle: Complete Mediation

- Common requirement: system must have ability to mediate all security-relevant operations
  - Dangerous to assume op is not security-relevant..
  - Many places to mediate: hardware, compiler, …
- Assumption: mediation mechanism cannot be compromised (TCB)
- Example: operating system calls
  - Kernel interface mediates access to files, memory pages, etc.
  - No other way to create/manipulate resources
  - One problem: covert timing channels

Principle: Minimize TCB

- Observation: Complex things are more likely not to work correctly

Economy of Mechanism: Make trusted computing base as small and simple as possible.

"Things should be made as simple as possible–but no simpler."
-- *A. Einstein*

- Fewer errors in implementation, easier to convince someone that it's correct
- Corollary: Failsafe Defaults
  - Access should be off by default, explicitly enabled

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Principle: Least Privilege

- A principal should be given only those privileges needed to accomplish its tasks.
  - No more, no less.
- What is the minimal set of privileges?
- What is the granularity of privileges?
  - Separation of privileges (read vs. write access)
- How & when do the privileges change?

- Example violation: UNIX sendmail has root privilege

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Principle: Open Design

- Success of mechanism should not depend on it being secret
  - "No security through obscurity"
  - The only secrets are cryptographic keys
  - Increased assurance if many critics.
- An age-old controversy:
  - Open design makes critics' jobs easier, but also attackers' job.
  - Analysis tends to concentrate on core functionality; vulnerabilities remain off the beaten path. (Ergo: small TCB)

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Principle: Security is a Process

- Every system has vulnerabilities
  - Impossible to eliminate all of them
  - Goal: assurance
- Systems change over time
  - Security requirements change over time
  - Context of mechanisms changes over time
- Secure systems require maintenance
  - Check for defunct users
  - Update virus software
  - Patch security holes
  - Test firewalls

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Conventional security mechanisms

- Access control, encryption, firewalls, memory protection, …
- What are they?
- What are they good for?
- Where do they fall short?

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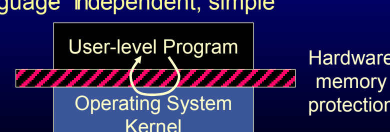
Operating system security

- Program is black box
- Program talks to OS via mediating interface (system calls)
  - Multiplex hardware
  - Isolate processes from each other
  - Restrict access to persistent data (files)
- + Language-independent, simple



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Weaknesses

- Treating the program as a black box
  - Not fine-grained enough to enforce desired properties
  - No help with validation
  - Internal behavior of program is important!

Reference Monitor

Observes the execution of a program and halts the program if it's going to violate the security policy

Common Examples:
- memory protection
- access control checks
- routers
- firewalls

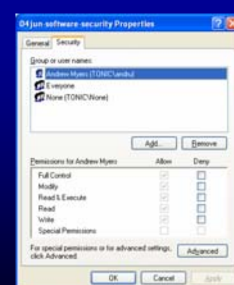
Most current enforcement mechanisms are reference monitors

Access control

- A mechanism for controlling which actions are permitted
- Assumes a reference monitor
- Can enforce safety properties
- Local but not system-wide enforcement of confidentiality and integrity

ACLs

- Access control list maps principals to their privileges
- Reference monitor checks relevant operations against ACL
- Works well if
  - Privileges have right granularity
  - System is not too complex



Capabilities

- Capability is an object that confers privileges to the possessor
- Important property:
  capabilities cannot be forged
- Different capability representations
  - Cryptographically strong pseudorandom number
  - Held by operating system ala file descriptors (Mach)
  - Object reference (Java)
- Advantage: allows privileges to be delegated even outside local system
  - Hard to keep capabilities from leaking out
  - Revoking capabilities can be difficult, expensive
  - E.g., X.509

Java: objects as capabilities

- Single Java VM may contain processes with different levels of privilege (e.g. different applets)
- Some objects are capabilities to perform security-relevant operations:

```
FileReader f = new FileReader("/etc/passwd");
// now use "f" to read password file
```

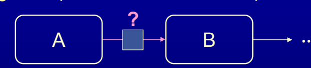
- Original 1.0 security model: use type safety, encapsulation to prevent untrusted applets from accessing capabilities in same VM
- Problem: tricky to prevent capabilities from leaking (downcasts, reflection, …)

Mandatory access control

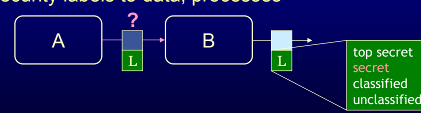
- Ordinary access control only protects information at point of access
- Confidentiality: program may leak information after it reads
- Integrity: program may overwrite with data from untrustworthy sources

Mandatory access control

- Discretionary access control: no control of propagation (at discretion of reader)



- Mandatory access control/multilevel security: attach security labels to data, processes



- Data from process with label L has label L

MAC Problems

- Read from a location with higher security label either:
  - Is rejected (no read-up / simple security property)
  - Raises the label of the process
- Write to a location with a lower security label either:
  - Is rejected (no write-down / *-property)
  - Raises the label of the location

- No write-down is awkward
- Label creep makes data unusable
- Expensive
- Not used much!

Cryptography (very briefly)

- Can construct algorithms that compute functions f such that x cannot be recovered from f(x)
- Keys k parameterize general algorithms (E,D)
- Shared-key cryptography: E(k) is inverse of D(k)
  - D(k, E(k, m)) = m
  - Example: DES
  - Problem: distributing shared keys securely
- Public-key cryptography: $E(k_e)$ is inverse of $D(k_d)$, but cannot find k_d even given k_e
  - $D(k_d, E(k_e, m)) = m = E(k_e, D(k_d, m))$
  - k_e is public key, k_d is corresponding secret key
  - Example: RSA
  - Problem: expensive
- Secure hashing: m cannot be recovered from H(m)
  - Example: MD5

Using cryptography

- Encryption:
  - E(k, m) keeps m from those who do not have key k : protects confidentiality
  - E(k, m) or D(k,m) can convince that you have k
  - $E(k_e, m)$ keeps m secret from those who do not have k_d (and sender doesn't need a secret)
    - Makes key distribution much easier
- Digital signatures:
  - $D(k_d, m)$ proves that message came from principal holding k_e
  - Anyone can check because $m = E(k_e, D(k_d, m))$
  - Provides authentication, integrity, nonrepudation
  - Public keys stand for principals

Intrusion detection?

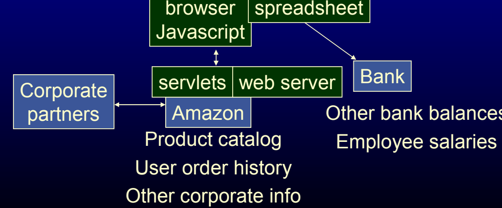
- Monitor behavior of programs and take remedial action if behavior is malicious or suspicious (anomaly detection)
  - Signal to operator, halt processes, roll back changes…
  - Can monitor at any level supporting mediation
- Inspired by biological systems
- Problems:
  - False alarms
  - Run-time overhead
  - Instability/autoimmune disease
  - Argument for higher assurance?
    - We do this anyway – but tools help!

Virus scanning?

- Scan for suspicious code
  - e.g., McAfee, Norton, etc.
  - based largely on a lexical signature.
  - the most effective commercial tool
  - but only works for things you've seen
    - Melissa spread in a matter of hours
  - virus kits make it easy to disguise a virus
    - "polymorphic" viruses
- Doesn't help as much with worms
  (some network-packet scanning tools)

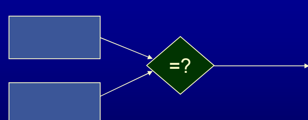
Distribution/partitioning

- Computation in general involves cooperation between mutually distrustful principals
- Securely place computation, data

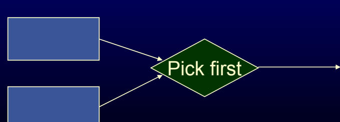


Replication

- Can improve integrity at the expense of availability:

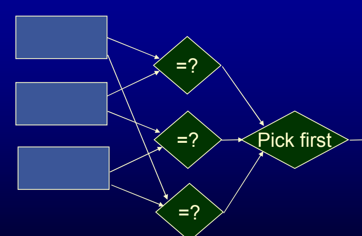


- Can improve availability at the expense of integrity:



Replication

- Can improve both:



- Quorum systems, etc.

Rollback/Undo

- Many systems (esp. databases) have a that records all changes made during a transaction
- Used to make transactions appear atomic
- Idea: use log to roll back changes

Interposition

- Complete mediation: should be able to intercept security-relevant operations
- May not know what is security-relevant at design time
  - Systems evolve and are used in unexpected ways
- Need general mechanisms for extensible mediation
  - Virtual machine monitors (e.g., VMware)
  - Software virtual machines
  - Program transformation (sandboxing/SFI, inlined reference monitors)
- Problem: recognizable operations may be at wrong level of abstraction

Information Flow Security

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End-to-end security

- Near-term problem: ensuring programs are memory-safe, type-safe so fine-grained access control policies can be enforced
- Long-term problem: ensuring that complex (distributed) computing systems enforce end-to-end information security policies
  - Confidentiality
  - Integrity
  - Availability
- Confidentiality, integrity: end-to-end, security described by information-flow policies

Information security: confidentiality

- Simple (access control) version:
  - Only authorized processes can read a file
  - But… when should a process be "authorized" ?
  - Encryption provides end-to-end confidentiality—if no computation
- End-to-end version:
  - Information should not be improperly released by a computation no matter how it is used
  - Requires tracking information flow

Information security: integrity

- Simple (access control) version:
  - Only authorized processes can write a file
  - But… when should a process be "authorized" ?
  - Digital signatures provide end-to-end integrity—if no computation
- End-to-end version:
  - Information should not be updated on the basis of less trustworthy information

Intensional vs. extensional security

- Access control is intensional: security requirements expressed in terms of program artifacts
  - Authority of processes and programs
  - File permissions
- Information flow is (ideally) extensional – regulates observable behavior of program rather than internals

Information channels

- End-to-end security requires controlling information channels [Lampson73]
- Storage channels: explicit information transmission (writes to sockets, files, variable assignments)
- Covert channels: transmit by mechanisms not intended for signaling information (system load, run time, locks)
- Timing channels: transmit information by *when* something happens (rather than what)

Implicit flows

- Covert storage channels arising from control flow. Example:

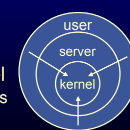
```
boolean b := <some secret>
if (b) {
  x = true; f();
}
```

- Creates information flow from b to x
- Run time check requires whole process labeled secret after branch

Multilevel security (MLS)

- Originally, computers, networks segregated by security class of information used
  - E.g., information could go from unclassified network to classified network but not vice versa
- Idea: build one system that can securely manipulate information of different classes
  - Multilevel secure: goal is end-to-end secrecy
  - Mandatory access control one possible
- One attempt: Multics/AIM ring model
  - Protects kernel from users, but not users

top secret
secret
classified
unclassified



Multilevel security policies

[Feiertag et al., 1977]

- Security level is a pair (A,C) where A is from a totally ordered set (unclassified, …) and C is a set of categories
- Example: data labeled (secret, {nuclear}) is less confidential than (top secret, {nuclear, iraq}) but incomparable to (secret, {iraq})

$$(A_1,C_1) \sqsubseteq (A_2,C_2) \text{ iff } A_1 \le A_2 \;\&\; C_1 \subseteq C_2$$

Ordering security policies

[Denning, 1976]

- Information flow policies (security policies in general) are naturally partial orders
  - If policy P_2 is at least as strong as P_1, write $P_1 \sqsubseteq P_2$
    - P1 = "smoking is forbidden in restaurants"
    - P2 = "smoking is forbidden in all public places"
  - Some policies are incomparable: $P_1 \not\sqsubseteq P_2$ and $P_2 \not\sqsubseteq P_1$
    - P2 = "keep off the grass"

P_2
|
P_1

Lattices

- Suppose there is always a least restrictive policy as least as strong as any two policies: $P_1 \sqcup P_2$ = "join" or least upper bound of P_1, P_2
  - $P_1 \sqcup P_2$ = "smoking is forbidden in restaurants and keep off the grass"
- Simplest policy system is boolean lattice:
  $L \sqsubseteq H$, $H \sqcup H = H$, $L \sqcup L = L$, $L \sqcup H = H$
- If have greatest lower bound too, policies form lattice. Supports reasoning about information channels that merge and split ($\sqcup$=LUB, $\sqcap$=GLB)

H
|
L

`c := a + b`	$L_a \sqcup L_b \sqsubseteq L_c$
`a := c; b := c`	$L_c \sqsubseteq L_a \sqcap L_b$

Generalizing levels to lattices

- Security levels may in general form a lattice (or just a partial order)
- $L_1 \sqsubseteq L_2$ means information can flow from level L_1 to level L_2
  - L_2 describes greater confidentiality requirements

Integrity

[Neumann et al., 1976; Biba, 1977]

- Integrity can also be described as a label
- Prevent: bad data from affecting good data
- $L_1 \sqsubseteq L_2$ means information can flow from level L_1 to level L_2
  - L_2 describes lower integrity requirements
  - Lower integrity means use of data is more restricted
- Integrity is dual to confidentiality

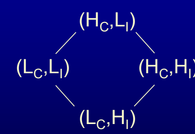
  Given: L_I, H_I are low, high integrity

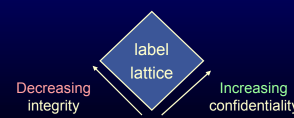
  L_C, H_C are low, high confidentiality

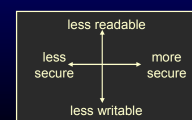
  $L_C \sqsubseteq H_C$ but $H_I \sqsubseteq L_I$

Combining properties

- Consider combined policy (C,I) governing both integrity and confidentiality:







Static analysis of information flow

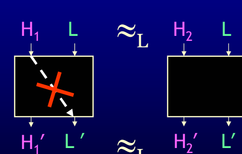
[Denning & Denning, 1977]

- Inference algorithm for determining whether variables are high or low
- Program counter label tracks implicit flows
  - Computed by dataflow analysis or type system

```
pc = ⊥  →
          boolean b := <some secret>
          if (b) {
pc = L_b →   x = true; f();
          }
pc = ⊥  →
```


Noninterference

- Low-security behavior of the program is not affected by any high-security data.
  [Cohen, 1977; Goguen & Meseguer 1982]
- An end-to-end, extensional definition of security



Confidentiality: high = confidential, low = public

Integrity: low = trusted, high = untrusted

A formalization

- Key idea: behaviors of the system C don't reveal more information than the low inputs
- Consider applying C to inputs s. Define:
  - $[\![C]\!]\, s$ is the result of C applied to input s
  - $s_1 =_L s_2$ means inputs s_1 and s_2 are indistinguishable to the low user at level L. E.g., $(H,L) \approx_L (H',L)$
  - $[\![C]\!] s_1 \approx_L [\![C]\!] s_2$ means results are indistinguishable : low view relation captures observational power

Noninterference of C: $s_1 =_L s_2 \;\Rightarrow\; [\![C]\!] s_1 \approx_L [\![C]\!] s_2$

"Low observer doesn't learn anything new from execution"

Downgrading & declassification

- Noninterference is too strong
  - Programs release confidential information as part of proper function
- Idea: add escape hatch mechanism that allows system to move data labels downward
- Weakening confidentiality restrictions: declassification
- Example: logging in using a secure password

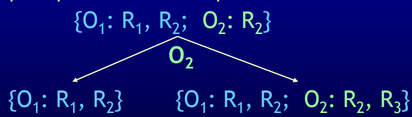
```
if (password == input) login();
  else report_failure();
```

  - Information about the password unavoidably leaks
  - Solution: declassify result of comparison

Decentralized Label Model

[ML97]

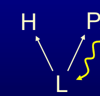
- Idea: use access control to control what declassifications are allowed
- Principals own parts of labels
- A principal can rewrite its part of the label



- Declassifying code must be trusted by owner
- Other owners' policies still respected

Intransitive noninterference

- INI policy augments label lattice with special downgrading arcs
- Password example:
  Password: label P
  Other confidential data: label H
  Public data: label L



- Declassification only allowed along arcs

Endorsement

- Dual of declassification: upgrades integrity
- Example: averaging a lot of untrusted data may produce a more trusted result
- Problem: noninterference doesn't hold in presence of downgrading; no equivalently compelling extensional property
  - INI, selective declassification focus attention on security-relevant downgrading operations

Robust declassification [ZM01, MSZ04]

- What can we say about end-to-end behavior in presence of declassification?
- One desirable property: untrusted data should not affect what data is released
  - otherwise attackers may be able to control what is released or whether something is released

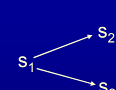
Defining robustness

- Let $C[a]$ be result of replacing low-integrity code in C with attack code a, $[\![C]\!]s$ is result of C applied to s
- Robustness:

$\forall s_1, s_2, a, a'.\ \ s_1 =_L s_2 \Rightarrow$
$[\![C[a]]\!]s_1 \approx_L [\![C[a]]\!]s_2 \Rightarrow [\![C[a']]\!]s_1 \approx_L [\![C[a']]\!]s_2$
"Attacker learns nothing more by changing attack"

- Can be enforced using static analysis: require inputs to declassification are high integrity
- Qualified robustness permits untrusted sources to affect declassification in limited ways; important for modeling real apps

Nondeterminism



- What if the system is nondeterministic?
  - Concurrency $(s_1 \mid s_2) \rightarrow (s_1' \mid s_2)$ *or* $(s_1 \mid s_2')$
  - Nondeterministic choice $(s_1 \Box s_2) \rightarrow s_1$ *or* s_2
  - Lack of knowledge about inputs, environment read() → ?

Noninterference: $s_1 =_L s_2 \Rightarrow [\![C]\!]s_1 \approx_L [\![C]\!]s_2$

What if there are multiple possible results?

Possibilistic security

[Sutherland 1986, McCullough 1987]

- Result of a system $[\![C]\!]s$ is set of possible outcomes τ
  - Outcome could be a trace $\tau = s \rightarrow s' \rightarrow s'' \rightarrow \ldots$
- Low view relation on traces is lifted to sets of traces:

$$[\![C]\!]s_1 \approx_L [\![C]\!]s_2 \text{ if}$$

$$\forall\tau_1\in[\![C]\!]s_1 \,.\, \exists\tau_2\in[\![C]\!]s_2 \,.\, \tau_1 \approx_L \tau_2 \ \& $$
$$\forall\tau_2\in[\![C]\!]s_2 \,.\, \exists\tau_1\in[\![C]\!]s_1 \,.\, \tau_2 \approx_L \tau_1$$

"For any result produced by C_1 there is an indistinguishable one produced by C_2 (and vice-versa)"

Example

```
l := true | l := false | l := h
```

`h`=true`:` possible results are

{`h`↦true, `l`↦false}, {`h`↦true, `l`↦true}

$=_L$ $=_L$

`h` = false:

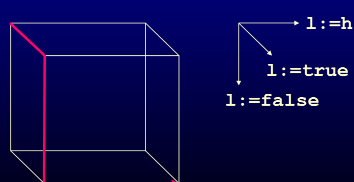
{`h`↦false, `l`↦false}, {`h`↦false, `l`↦true}

- Program is possibilistically secure

What is wrong?

- Round-robin scheduler: program equiv. to `l:=h`
- Random scheduler: `h` most probable value of `l`
- System has a refinement with information leak

```
l := true | l := false | l := h
```



Low-view observational determinism

- Result of a system $[\![C]\!]s$ is set of possible outcomes τ
  - Outcome could be a trace $\tau = s \rightarrow s' \rightarrow s'' \rightarrow \ldots$
- Low view relation on traces is lifted to sets of traces:

$$[\![C]\!]s_1 \approx_L [\![C]\!]s_2 \text{ if}$$
$$\forall\tau_1\in[\![C]\!]s_1 \,.\, \forall\tau_2\in[\![C]\!]s_2 \,.\, \tau_1 \approx_L \tau_2$$

"All results produced by C_1 and C_2 are indistinguishable"

- Can apply to concurrent systems [ZM03]

Conclusions

- Information flow yields a way of talking about end-to-end security properties
- Noninterference: an extensional property enforceable by static analysis
- Neat idea, still not used much in practice
- Some open areas:
  - Dealing with information release
    - Security in the presence of downgrading
    - Connection to access control
  - Information flow in concurrent and distributed systems
  - Application to richer security policies (privacy, anonymity,…)