4. OS Protection Mechanisms

ENEE 657

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http://ter.ps/enee657

Today's Lecture

- Where we've been
  - Memory corruption exploits
  - Cryptography
- Where we're going today
  - Separation of Privileges
  - Confinement
  - Implementation of OS protection mechanisms
  - **Pilot project proposals due today!**
- Where we're going next
  - Security analytics lab
  - Next week: Network security basics

Pilot Project Proposals

- Due **today at midnight**
  - **Post proposal** on the **Piazza** discussion board
  - Some ideas available on the class Web page
- Proposal should be concise (**2-3 paragraphs**)
  - Problem statement
  - Approach considered for tackling the problem
    - Must describe **concrete tasks**, not vague directions
    - Must **demonstrate that you've thought about the first steps**, and you are not simply paraphrasing the project ideas I gave you

Goals of Security Mechanisms

- Eliminate an **entire class** of attacks
  - Example: harvesting credit card numbers by sniffing network packets used to be common in the '90s. HTTPS stopped that.
  - Challenges:
    - **Arms race**: adversaries find new attacks (e.g., harvesting credit card numbers by hacking point-of-sale systems)
    - Mechanism may not address the **capabilities of real-world adversaries** (we've seen: attacking crypto without breaking the math)
- Make it **less likely** for an attack to succeed
  - Increases the attacker's **work factor**
  - Requires understanding attack techniques
- **Distinguish** between benign and malicious behavior
  - Increasingly using **statistical techniques**

Statistical Inference

- You must understand how to interpret data correctly
- Statistical inference: Methods for drawing conclusions about a population from sample data
- Two key methods
  - Confidence intervals
  - Hypothesis tests (significance tests)

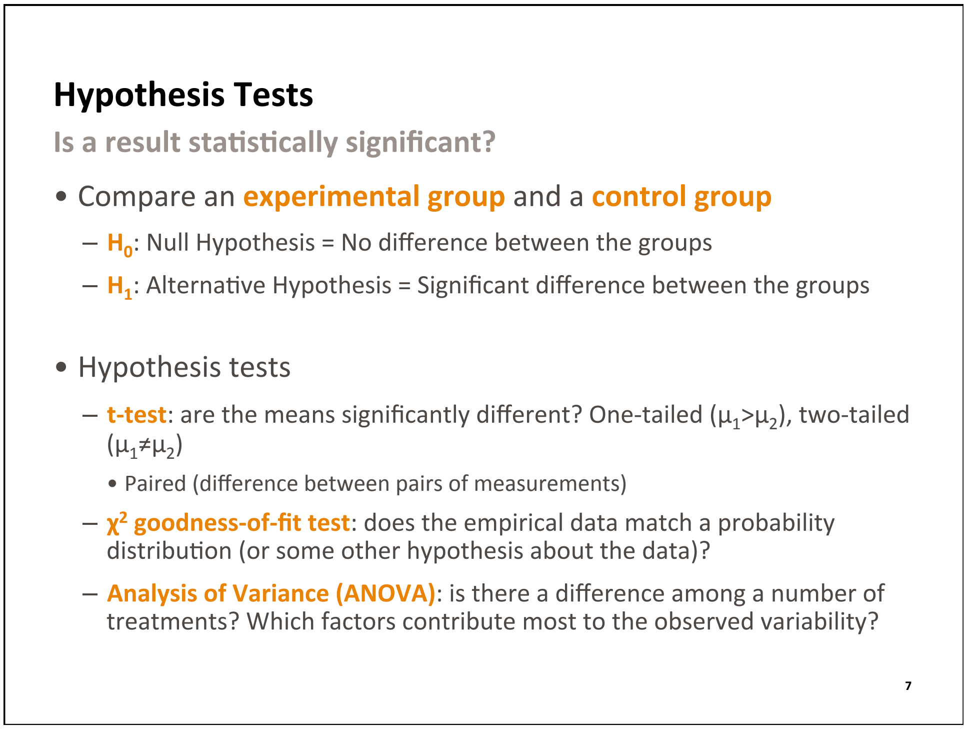
Confidence Intervals

What is the range of likely values?

- 95% confidence interval for the sample mean
  - If we repeated the experiment 100 times, we expect that this interval would include the mean 95/100 times
  - $CI = \mu \pm 1.96 \frac{\sigma}{\sqrt{n}}$

μ: mean
σ: standard deviation
n: number of elements

- Why 95%?
  - No good reason, but widely used
- You can compute confidence intervals for many statistical measures
  - Variance, slope of regression line, effect size, etc.

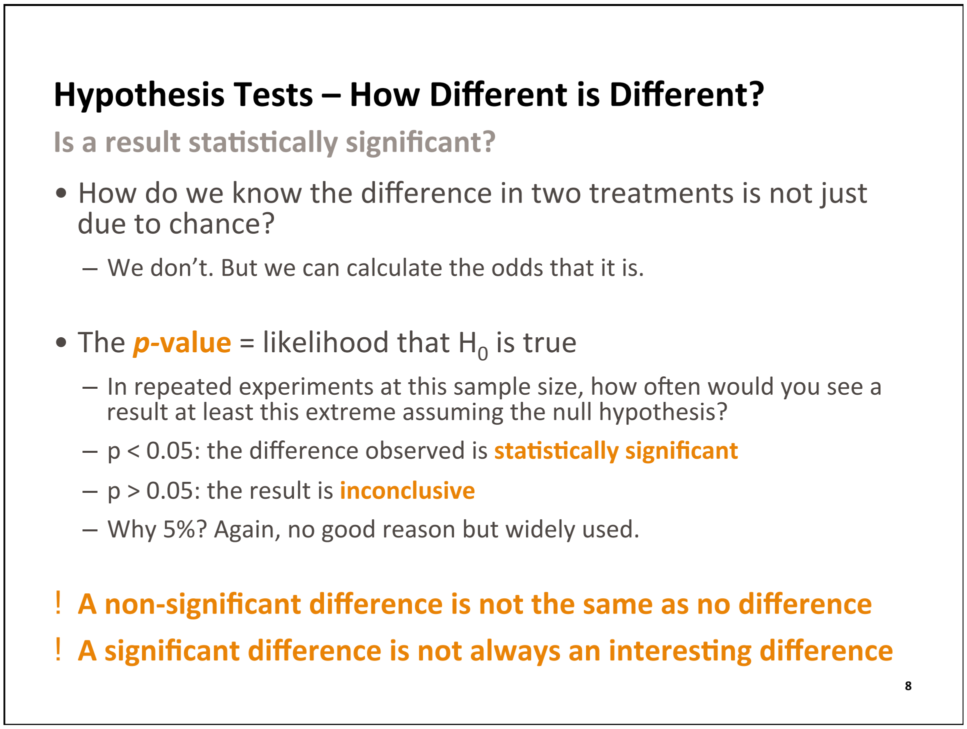


Hypothesis Tests

Is a result statistically significant?

- Compare an **experimental group** and a **control group**
  - **H_0**: Null Hypothesis = No difference between the groups
  - **H_1**: Alternative Hypothesis = Significant difference between the groups

- Hypothesis tests
  - **t-test**: are the means significantly different? One-tailed ($\mu_1 > \mu_2$), two-tailed ($\mu_1 \neq \mu_2$)
    - Paired (difference between pairs of measurements)
  - **χ^2 goodness-of-fit test**: does the empirical data match a probability distribution (or some other hypothesis about the data)?
  - **Analysis of Variance (ANOVA)**: is there a difference among a number of treatments? Which factors contribute most to the observed variability?



Hypothesis Tests – How Different is Different?

Is a result statistically significant?

- How do we know the difference in two treatments is not just due to chance?
  - We don't. But we can calculate the odds that it is.

- The ***p*-value** = likelihood that H_0 is true
  - In repeated experiments at this sample size, how often would you see a result at least this extreme assuming the null hypothesis?
  - $p < 0.05$: the difference observed is **statistically significant**
  - $p > 0.05$: the result is **inconclusive**
  - Why 5%? Again, no good reason but widely used.

! **A non-significant difference is not the same as no difference**

! **A significant difference is not always an interesting difference**

Confusion Matrix

How to determine if your attack detector does a good job?

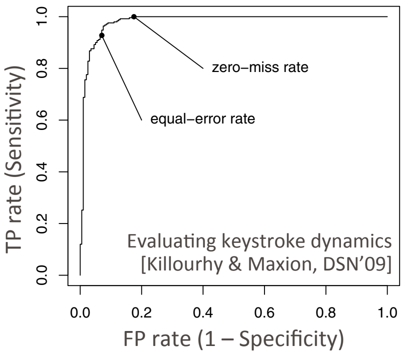
- You need a training set (ground truth) and a testing set
  - Or you can split your ground truth into two data sets
  - Even better: K-fold cross-validation
    - Select K samples without replacement and train classifier multiple times
- You can make a mistake in two different ways

	True -	**True +**
Predicted -	True Negative (TN) *Correct decision*	**False Negative** (FN) *Type 2 error*
Predicted +	**False Positive** (FP) *Type 1 error*	True Positive (TP) *Correct decision*

Evaluating Results

Is it better to have low FPs or low FNs?

- There is usually a **trade-off** between FPs and FNs
  - Reducing type 1 errors causes more type 2 errors, and vice-versa
- **Sensitivity** = TP / (TP+FN)
  - Ability to identify true positives
  - Also called true positive rate
- **Specificity** = TN / (FP + TN)
  - Ability to rule out true negatives
  - Also called true negative rate



Evaluating keystroke dynamics [Killourhy & Maxion, DSN'09]

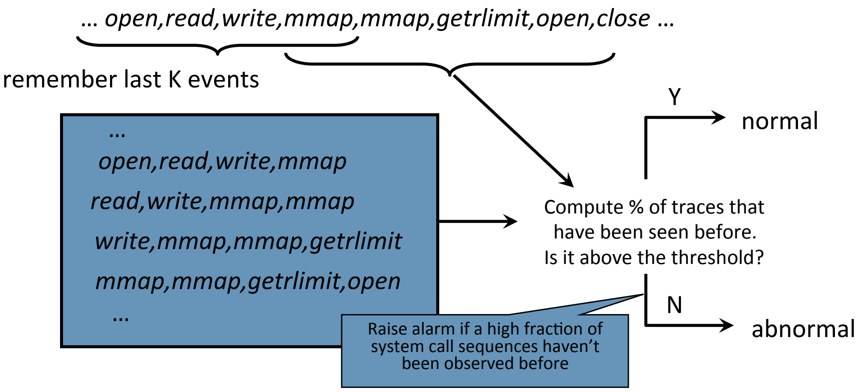
Detecting Attacks and Intrusions

- Observation: to damage host system (e.g. persistent changes) app must make **system calls**:
  - To delete/overwrite files: unlink, open, write
  - To do network attacks: socket, bind, connect, send
- Idea: monitor all system calls and block those that violate **security policy**
  - Language-level: Java runtime environment inspects the stack of the function attempting to access a sensitive resource and checks whether it is permitted to do so
  - OS-level: system call wrapper (more on this in a bit)
  - How do you establish the security policy?

Example: "Immunology" Approach

[Forrest et al., IEEE S&P'96]

- Normal profile: short **sequences of system calls**
  - Use strace on UNIX
- Compute statistical properties and report **anomalies**
  - More on this later



… *open,read,write,mmap,mmap,getrlimit,open,close* …

remember last K events

…
open,read,write,mmap
read,write,mmap,mmap
write,mmap,mmap,getrlimit
mmap,mmap,getrlimit,open
…

Compute % of traces that have been seen before.
Is it above the threshold?

Raise alarm if a high fraction of system call sequences haven't been observed before

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      (e.g., harvesting credit card numbers by hacking point-of-sale systems)
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      (we’ve seen: attacking crypto without breaking the math)
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Principle of Least Privilege

- What’s a privilege?
  - Ability to access or modify a resource
- System has multiple users
  - And multiple components (more on in a bit)
- **Principle of Least Privilege**
  - A user should only have the minimal privileges needed to do his/her work
  - Same for system components

OS Security Model

- Isolation between processes
  - Each process has a user (UID)
    - Two processes with same UID have same permissions
  - A process may access files, network sockets, ….
    - Permission granted according to UID
- Access control matrix [Lampson]

Resources

Principals

	File 1	File 2	File 3	…	File n
User 1	read	write	-	-	read
User 2	write	write	write	-	-
User 3	-	-	-	read	read
…					
User m	read	write	read	write	read

Implementation Requirements

Key component: **reference monitor**

- **Mediates requests** from applications
  - Implements protection policy
  - Enforces isolation and confinement
- Must **always** be invoked:
  - Every application request must be mediated
- **Tamperproof**:
  - Reference monitor cannot be killed
  - … or if killed, then monitored process is killed too
- **Small enough** to be analyzed and validated

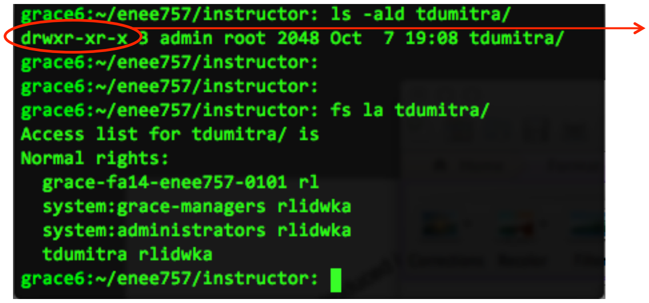
Implementation Concept #1: Access Control Lists

- Access control list (**ACL**)
  - Store column of matrix with resource
  - Relies on authentication: need to know user
  - Delegation: let other process act under current user
    - UNIX su/sudo, Windows UAC

	File 1	File 2	…
User 1	read	write	-
User 2	write	write	-
User 3	-	-	read
…			
User m	Read	write	write

ACL: store in filesystem metadata

UNIX Access Control Lists



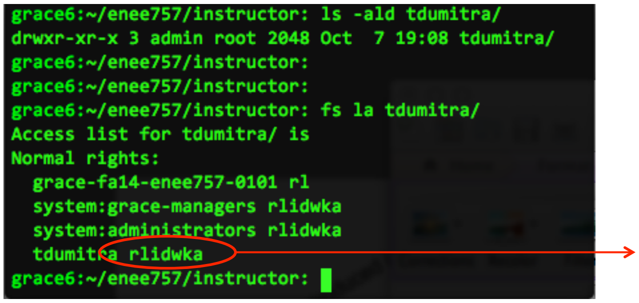
```
grace6:~/enee757/instructor: ls -ald tdumitra/
drwxr-xr-x 3 admin root 2048 Oct  7 19:08 tdumitra/
grace6:~/enee757/instructor:
grace6:~/enee757/instructor:
grace6:~/enee757/instructor: fs la tdumitra/
Access list for tdumitra/ is
Normal rights:
  grace-fa14-enee757-0101 rl
  system:grace-managers rlidwka
  system:administrators rlidwka
  tdumitra rlidwka
grace6:~/enee757/instructor: 
```

UNIX permissions:

$\underbrace{\text{rwx}}_{\text{ownr}}\ \underbrace{\text{rwx}}_{\text{grp}}\ \underbrace{\text{rwx}}_{\text{othr}}$

- UNIX permissions are designed for a single host that manages a local filesystem
  - UIDs: local users
  - Reference monitor: OS kernel

AFS Access Control Lists



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grace6:~/enee757/instructor:
grace6:~/enee757/instructor: fs la tdumitra/
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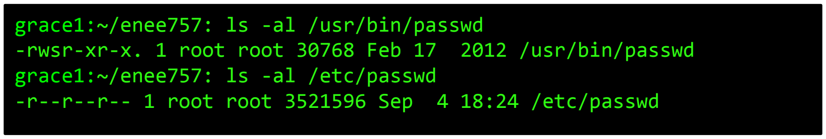
  system:grace-managers rlidwka
  system:administrators rlidwka
  tdumitra rlidwka
grace6:~/enee757/instructor: 
```

AFS permissions

- The Andrew File System (AFS) is a distributed filesystem
  - Precursor to cloud storage systems
  - Users divided into realms (e.g. UMD, CMU)
  - Reference monitor: file server

Set-id Bits on Executable Unix File

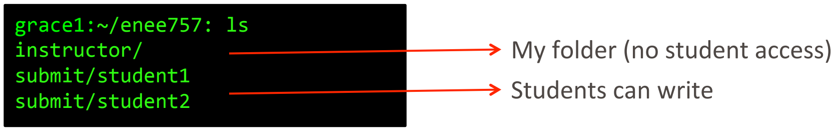
- Three set-id bits
  - Setuid – set EUID of process to ID of file owner
  - Setgid – set EGID of process to GID of file
  - Sticky
    - Off: if user has write permission on directory, can rename or remove files, even if not owner
    - On: only file owner, directory owner, and root can rename or remove file in the directory
- Why needed?



```
grace1:~/enee757: ls -al /usr/bin/passwd
-rwsr-xr-x. 1 root root 30768 Feb 17  2012 /usr/bin/passwd
grace1:~/enee757: ls -al /etc/passwd
-r--r--r-- 1 root root 3521596 Sep  4 18:24 /etc/passwd
```

The Confused Deputy Problem

- Say I want to write a script for students to submit assignments
  - `submit` is invoked by students, compiles and runs tests on the assignment, and places the results in a folder that I can read



```
grace1:~/enee757: ls
instructor/
submit/student1
submit/student2
```

My folder (no student access)

Students can write

- Say I also want the script to maintain a log file, for debugging
  - `submit` runs with the student's access control permissions
  - Different students cannot access each others' submissions
  - I want to keep the log in the `instructor/` folder
  - How can `submit` update the log file?

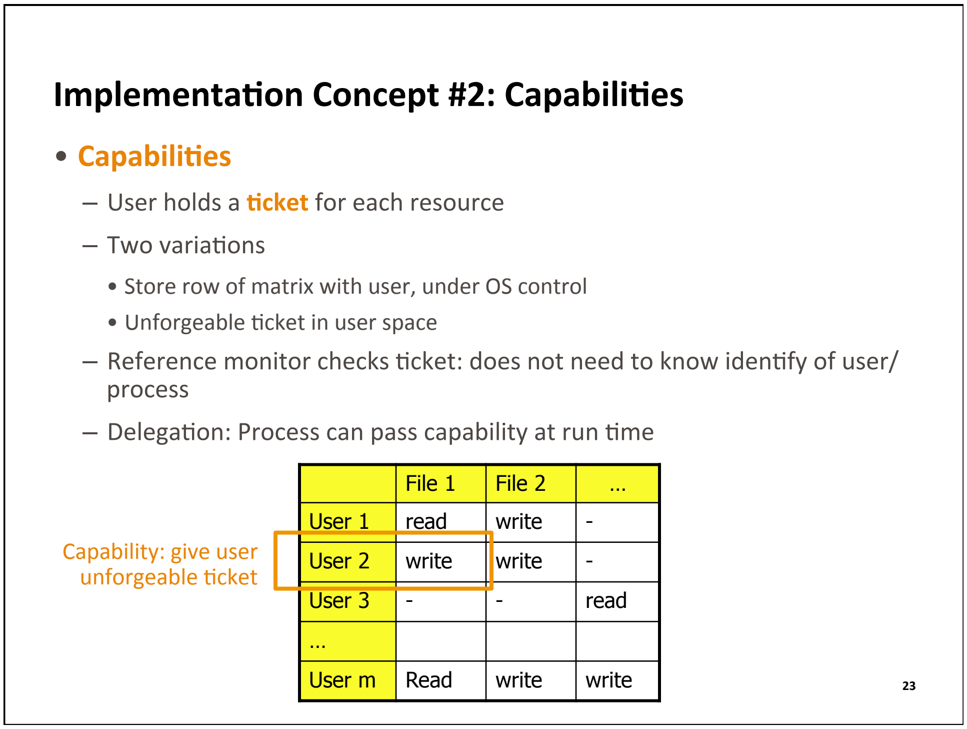
The Confused Deputy Problem – cont'd

[Hardy, 1988]

- I could make `submit` setuid-instructor
  - At runtime, the script acquires the permissions to write in `instructor/`
  - `submit` can update the logfile
    - Students are still unable to access files in `instructor/` directly
  - Can you see a problem with this?

- `submit` compiles and executes programs that students wrote!
  - A student may submit a program that modifies files in `instructor/` (say, the grade records)
    - Or exploit a vulnerability in my `submit` program to execute code

- The problem is that setuid grants access to all the files I can write (ambient authority)
  - I only wanted to grant write access to the log file
  - But this cannot be expressed in the ACL model!



Implementation Concept #2: Capabilities

- **Capabilities**
  - User holds a **ticket** for each resource
  - Two variations
    - Store row of matrix with user, under OS control
    - Unforgeable ticket in user space
  - Reference monitor checks ticket: does not need to know identify of user/process
  - Delegation: Process can pass capability at run time

Capability: give user unforgeable ticket

	File 1	File 2	…
User 1	read	write	-
User 2	write	write	-
User 3	-	-	read
…			
User m	Read	write	write

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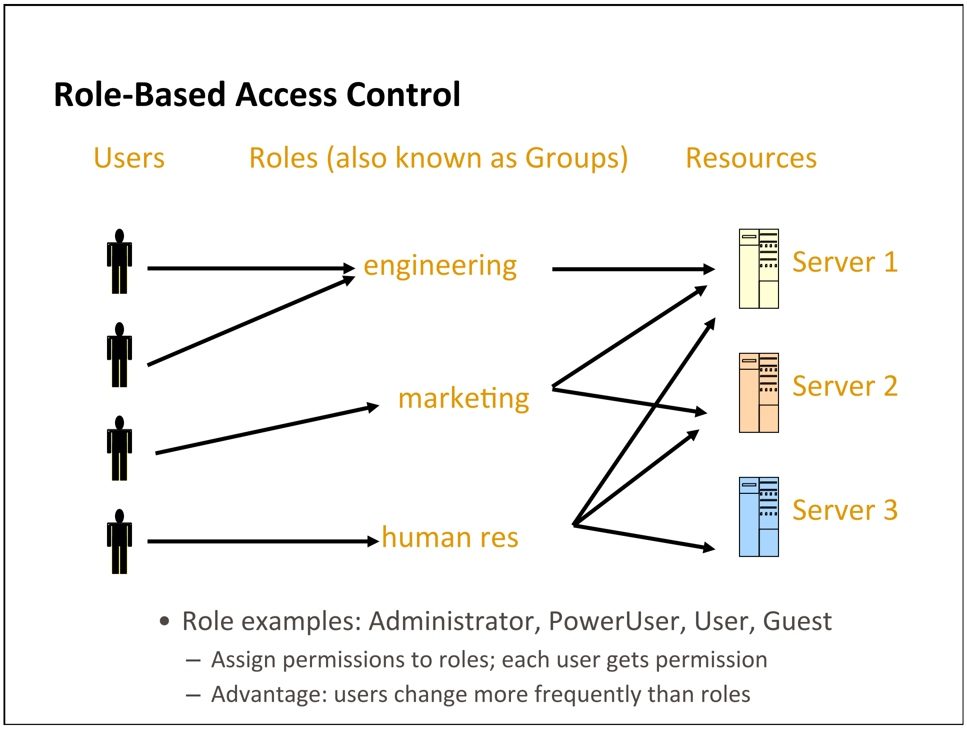


Role-Based Access Control

- Role examples: Administrator, PowerUser, User, Guest
  - Assign permissions to roles; each user gets permission
  - Advantage: users change more frequently than roles

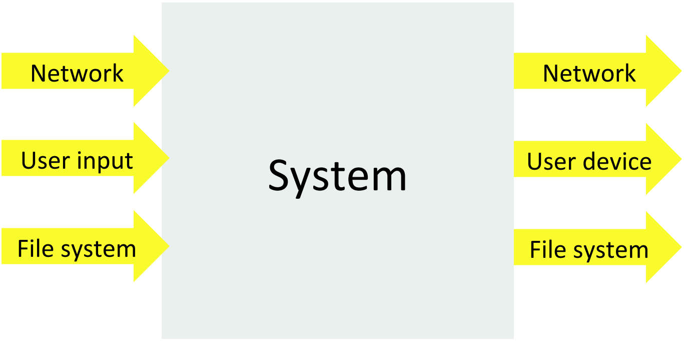
The Confinement Principle

- We've talked about file access control
  - What about other resources?

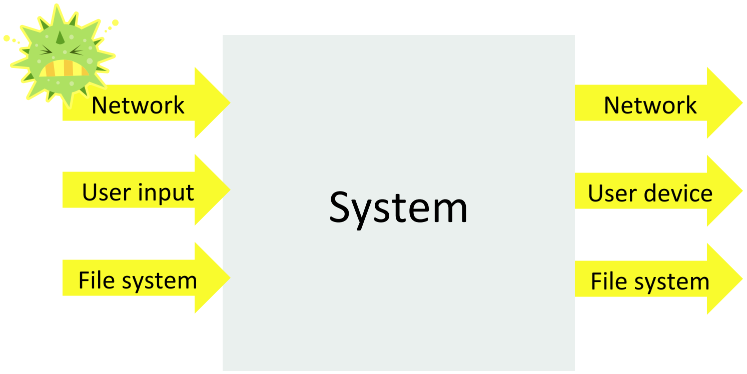
- We often need to run buggy/unstrusted code:
  - programs from untrusted Internet sites:
    - apps, extensions, plug-ins, codecs for media player
  - exposed applications: pdf viewers, outlook
  - legacy daemons: sendmail, bind
  - honeypots

Goal: if application "misbehaves" ⇒ kill it

Monolithic Design



Monolithic Design



Network

User input

File system

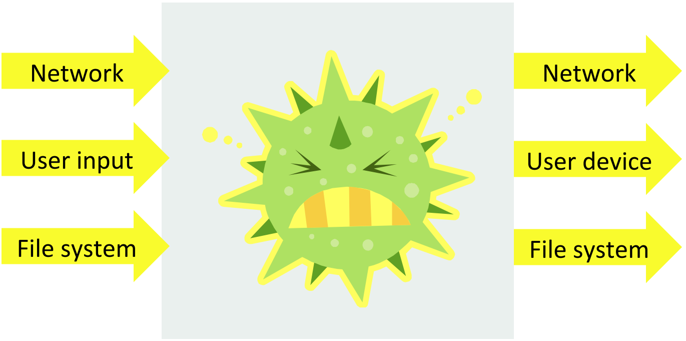
System

Network

User device

File system

Monolithic Design



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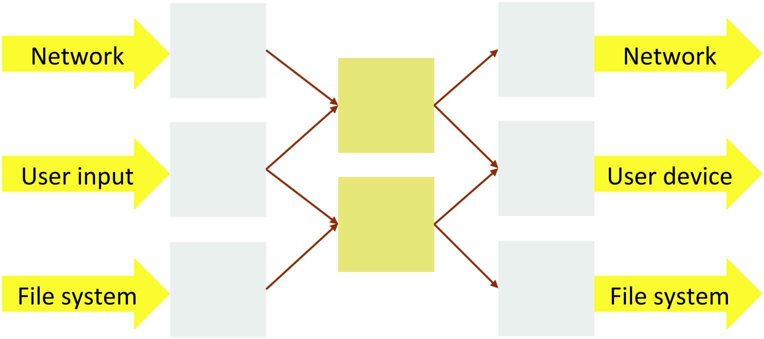
Component Design



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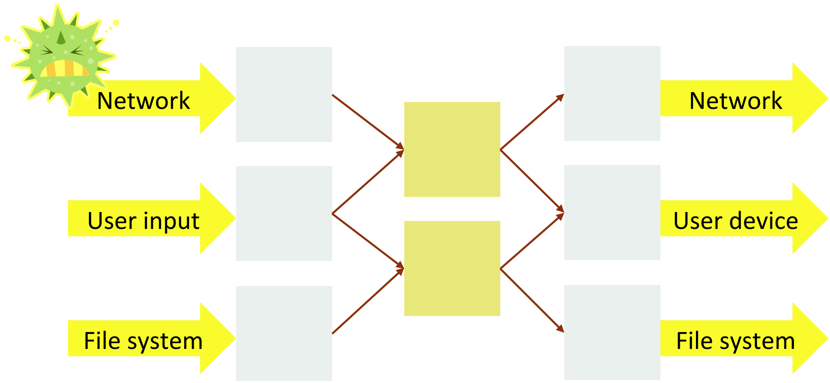

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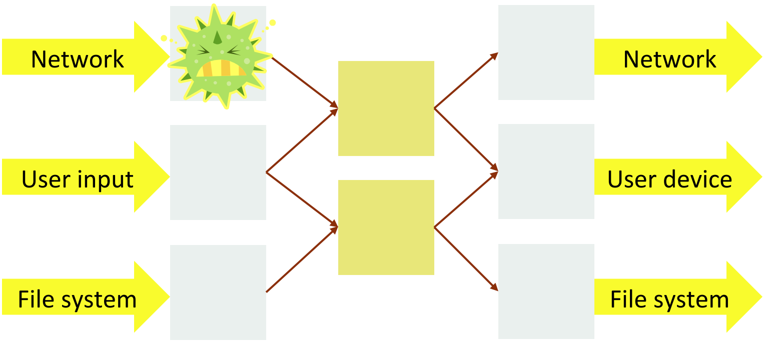
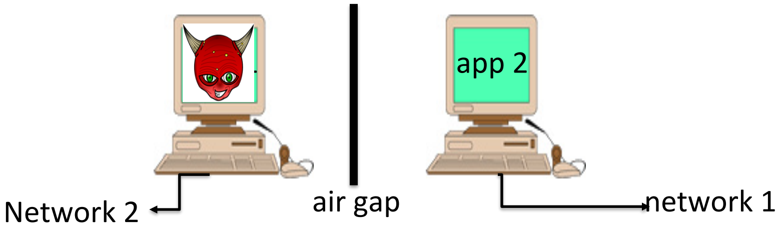


Implementing Confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Hardware**: run application on isolated hw (air gap)

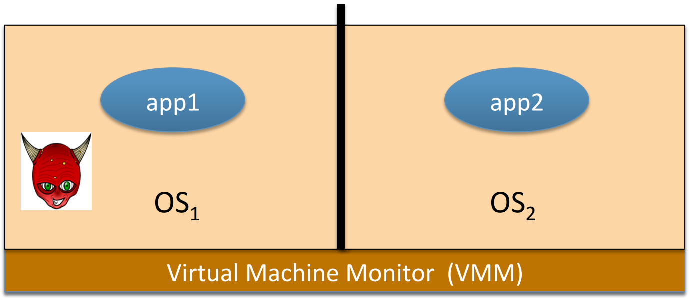


Implementing Confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Virtual machines**: isolate OS's on a single machine



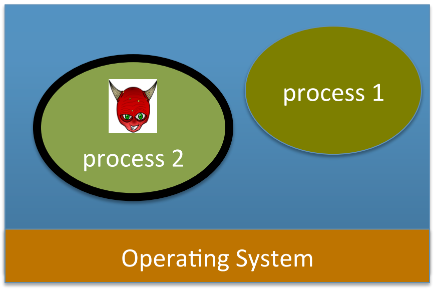
Implementing Confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Process:** System Call Interposition

  Isolate a process in a single operating system



Implementing Confinement

Confinement: ensure misbehaving app cannot harm rest of system

Can be implemented at many levels:

- **Threads:** Software Fault Isolation (SFI)
  - Isolating threads sharing same address space

- **Application**: e.g. browser-based confinement

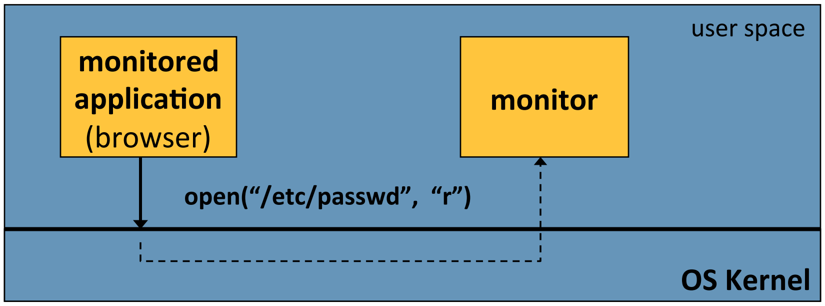
System Call Interposition

[Goldberg+, USENIX Security'96]

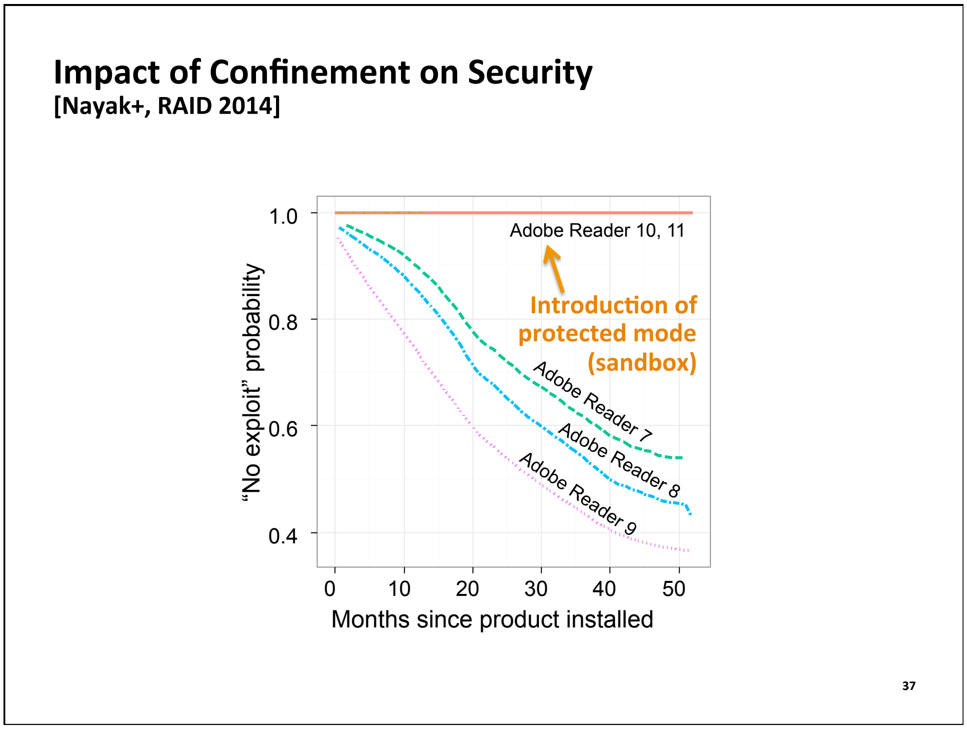
- Goal: monitor sys calls and block unauthorized calls
- Implemented with Linux **ptrace**: process tracing

process calls: **ptrace (… , pid_t pid , …)**

and wakes up when **pid** makes sys call



Challenge: how to establish policy for which calls to block?



Impact of Confinement on Security

[Nayak+, RAID 2014]

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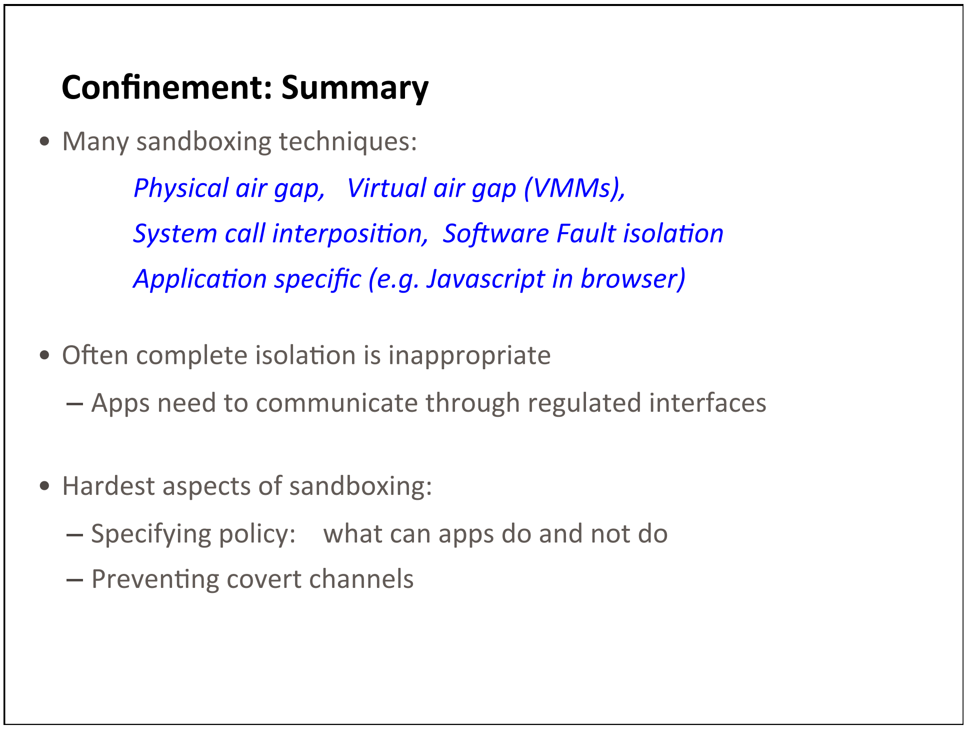


Confinement: Summary

- Many sandboxing techniques:

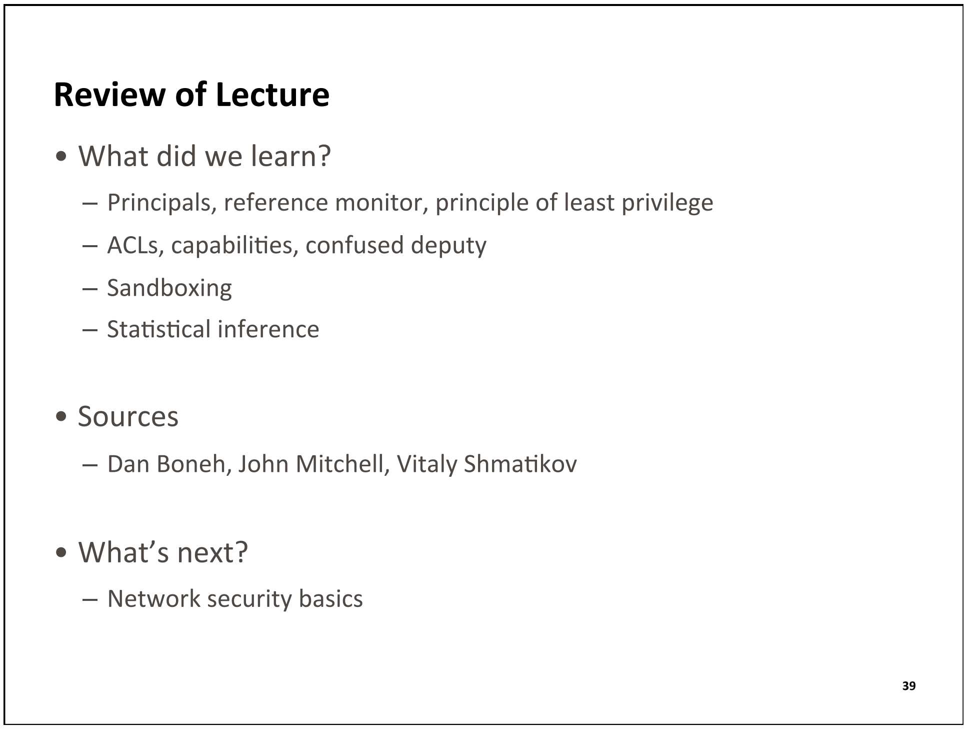
  Physical air gap, Virtual air gap (VMMs),

  System call interposition, Software Fault isolation

  Application specific (e.g. Javascript in browser)

- Often complete isolation is inappropriate
  – Apps need to communicate through regulated interfaces

- Hardest aspects of sandboxing:
  – Specifying policy: what can apps do and not do
  – Preventing covert channels



Review of Lecture

- What did we learn?
  - Principals, reference monitor, principle of least privilege
  - ACLs, capabilities, confused deputy
  - Sandboxing
  - Statistical inference
- Sources
  - Dan Boneh, John Mitchell, Vitaly Shmatikov
- What's next?
  - Network security basics