15-410

"...1969 > 1999?..."

Protection
Apr. 4, 2011

Dave Eckhardt

Hoax Alert

You have been the victims of a vast, intricate hoax

Hoax Alert

You have been the victims of a vast, intricate hoax

- **Friday's lecture accurately described key parts of the MIPS design principles and resulting implementation**

Hoax Alert

You have been the victims of a vast, intricate hoax

- **Friday's lecture accurately described key parts of the MIPS design principles and resulting implementation**
  - **Friday's lecture did *not* accurately describe Project 4**
    - **» (It will be something else)**

Hoax Alert

You have been the victims of a vast, intricate hoax

- **Friday's lecture accurately described key parts of the MIPS design principles and resulting implementation**
  - **Friday's lecture did *not* accurately describe Project 4**
    - » **(It will be something else)**
- **How could such a thing happen?**
  - **Friday was April 1st. Things got out of hand! But it was an excellent motivation for Joshua to write the lecture and the rest of us to pay close attention to it.**

Synchronization

Project 3 status poll

- Who is running tests?
- Who is confident of passing the hurdle by Friday? Monday?
- Who is passing "mostly everything" (excepting, e.g., cho)

Synchronization

Upcoming lectures

- Security, security
- Transactions
- Device drivers
- ...
- Exam review

Attendance is probably in your best interest

Synchronization

15-412 (Fall '11)

- If 410 was fun...
- If you want to do more,
- If you want to see how it's done “in real life”,
- If you want to write real OS code used by real people,
- Consider 15-412

15-610 (Spring '12)

- If you want hands-on experience with tricks of the trade
  - N mini-projects: hints, prefetching, transactions, ...
  - Small, intimate class
  - Achievable without panic

Outline

Protection (Chapter 14)

- Protection vs. Security
- Domains (Unix, Multics)
- Access Matrix
  - Concept, Implementation
- Revocation – not really covered today (see text)

Mentioning EROS

[Later lectures: techniques and cracks]

Protection vs. Security

Textbook's distinction

- **Protection happens inside a computer**
  - **Which parts may access which other parts (how)?**
- **Security considers *external threats***
  - **Is the system's model intact or compromised?**

Protection

Goals

- Prevent intentional attacks
- "Prove" *access policies* are always obeyed
- Detect bugs
  - "Wild pointer" example

Policy specifications

- System administrators
- Users - May want to add new privileges to system

Objects

Hardware

- Exclusive-use: printer, serial port, CD writer, ...
- Fluid aggregates: CPU, memory, disks, screen

Logical objects

- Files
- Processes
- TCP port 25
- Database tables

Operations

Depend on object!

- Disk: read_sector(), write_sector()
- CD-ROM: read_sector(...)
- TCP port: advertise(...)
- CPU
  - Conceptually: context_switch(...), <interrupt>
  - More sensibly: realtime_schedule(..., ...)

Access Control

Basic access control

- Your processes should access only “your stuff”
- Implemented by many systems

Access Control

Basic access control

- Your processes should access only “your stuff”
- Implemented by many systems

Principle of least privilege

- (text: “need-to-know”)
- `cc -c foo.c`
  - should read foo.c, stdio.h, ...
  - should write foo.o
  - *should not write ~/.cshrc*
- This is harder

Who Can Do What?

access right = (object, operations)

- /etc/passwd, r
- /etc/passwd, r/w

process ➔ protection domain

- P0 ➔ de0u, P1 ➔ garth, ...

protection domain ➔ list of access rights

- de0u ➔ (/etc/passwd, r), (/afs/andrew/usr/de0u/.cshrc, w)

Protection Domain Example

Domain 1

- /dev/null, read/write
- /usr/davide/.cshrc, read/write
- /usr/garth/.cshrc, read

Domain 2

- /dev/null, read/write
- /usr/garth/.cshrc, read/write
- /usr/davide/.cshrc, read

Using Protection Domains

Least privilege requires *domain changes*

- **Doing different jobs requires different privileges**
- **One printer daemon, N users**
  - **“Print each user's file with minimum necessary privileges...”**

Using Protection Domains

Least privilege requires *domain changes*

- Doing different jobs requires different privileges
- One printer daemon, N users
  - "Print each user's file with minimum necessary privileges..."

Two general approaches

- Hold constant the "process ➔ domain" mapping
  - Requires domains to add and drop privileges
  - User "printer" gets & releases permission to read your file
- Hold constant the privileges of a domain
  - Processes *domain-switch* between high-privilege, low-privilege domains
  - Printer *process* opens file as you, opens printer as "printer"

Protection Domain Models

Three sample models

- Domain = user
- Domain = process
- Domain = procedure
- (other models are possible)

Domain = User

Object permissions depend on *who you are*

All processes you are running share privileges

Privilege adjustment?

- **Log off, log on (i.e., domain switch)**

Domain = Process

Resources managed by special processes

- Printer daemon, file server process, ...

Privilege adjustment?

- Objects cross domain boundaries via IPC
- “Please send these bytes to the printer”

```
/* concept only; pieces missing */
s = socket(AF_UNIX, SOCK_STREAM, 0);
connect(s, pserver, sizeof pserver);
mh->cmsg_type = SCM_RIGHTS;
mh->cmsg_len[0] = open(“/my/file”, 0, 0);
sendmsg(s, &mh, 0);
```

Domain = Procedure

Processor limits access at fine grain

- ***Hardware protection on a per-variable*** **basis!**

Domain switch – *Inter-domain procedure call*

- **nr = print(strlen(buf), buf);**
- **What is the “correct domain” for print()?**
  - **Access to OS's data structures**
  - **Permission to call OS's internal `putbytes()`**
  - **Permission to read user's `buf`**

Domain = Procedure

Processor limits access at fine grain

- ***Hardware protection on a per-variable* basis!**

Domain switch – *Inter-domain procedure call*

- **nr = print(strlen(buf), buf);**
- **What is the “correct domain” for print()?**
  - **Access to OS's data structures**
  - **Permission to call OS's internal `putbytes()`**
  - **Permission to read user's `buf`**
- **Ideally, correct domain automatically created by hardware**
  - **Common case: “user mode” vs. “kernel mode”**
    - » **Only a rough approximation of the right domain**
    - » **But simple for hardware to implement**

Unix “setuid” concept

Assume Unix protection domain ≡ numeric user id

- Not the whole story! This overlooks:
  - Group id, group vector
  - Process group, controlling terminal
  - Superuser
- But let's pretend for today

Domain switch via *setuid executable*

- Special permission bit set with `chmod u+s file`
  - Meaning: exec() sets uid to executable file's owner
- Gatekeeper programs
  - “`lpr`” run by anybody can access `printer`'s queue files

Access Matrix Concept

Concept

- Formalization of “who can do what”

Basic idea

- Store all permissions in a matrix
  - One dimension is protection domains
  - Other dimension is objects
  - Entries are access rights

Access Matrix Concept

	File1	File2	File3	Printer
D1		rwxd	r	
D2	r		rwxd	w
D3	rwxd	rwxd	rwxd	w
D4	r	r	r	

Access Matrix Details

OS must still define process → domain mapping

OS must define, enforce domain-switching rules

- Ad-hoc approach
  - Special domain-switch rules (e.g., log off/on)
- Can encode domain-switch in access matrix!
  - Switching domains is a privilege like any other...
  - Add domain *columns* (domains are objects)
  - Add switch-to rights to domain objects
    - » "D2 processes can switch to D1 at will"
  - Subtle (dangerous)

Adding "Switch-Domain" Rights

	File1	File2	File3	D1
D1		rwxd	r	
D2	r		rwxd	s
D3	rwxd	rwxd	rwxd	
D4	r	r	r	

Updating the Matrix

Ad-hoc approach

- **“System administrator” can update matrix**

Matrix approach

- **Add *copy rights* to objects**
  - **“Domain D1 may copy read rights for File2”**
  - **So D1 can give D2 the right to read File2**

Adding Copy Rights

	File1	File2	File3
D1		rwxdR	r
D2	r		rwxd
D3	rwxd	rwxd	rwxd
D4	r	r	r

Adding Copy Rights

	File1	File2	File3
D1		rwxdR	r
D2	r	r	rwxd
D3	rwxd	rwxd	rwxd
D4	r	r	r

Updating the Matrix

Add *owner rights* to objects

- D1 has owner rights for O47
- D1 can modify the O47 column at will
  - Can add, delete rights to O47 from all other domains

Add *control rights* to domain objects

- D1 has control rights for D2
- D1 can modify D2's rights to any object
  - D1 may be teacher, parent, ...

Access Matrix Implementation

Implement matrix via matrix?

- Huge, messy, slow

Very **clumsy for...**

- "world readable file"
  - Need one entry per domain
  - Must fill rights in when creating new domain
- "private file"
  - Lots of blank squares
    - » Can Alice read the file? - No
    - » Can Bob read the file? - No
    - » ...

Two typical approaches – "ACL", "capabilities"

Access Control List

File1	
D1	
D2	r
D3	rwxd
D4	r

Access Control List (ACL)

List per matrix column (object)

- de0u, read; garth, read+write

Naively, domain = user

AFS ACLs

- domain = user, user:group, system:anyuser, machine list (system:campushost)
- positive rights, negative rights
  - de0u:staff rlid
  - nwf   -id

Doesn't really do *least privilege*

- System stores *many* privileges per user, permanently...

Capability List

	File1	File2	File3
D1		rwxdR	r

Capability Lists

***Capability* Lists**

- **List per matrix row (domain)**
- **Naively, domain = user**
  - **More typically, domain = process**

Permit *least privilege*

- **Domains can transfer & forget capabilities**
  - **Possible to create “just right” domains**
    - » **cc which can't write to .cshrc**
- **Bootstrapping problem**
  - **Who gets which rights at boot?**
  - **Who gets which rights at login?**
  - **Typical solution: store capability lists in files somehow**

Mixed Approach

Permanently store ACL for each file

- **Must fetch ACL from disk to access file**
- **ACL fetch & evaluation may be long, complicated**

open() checks ACL, creates capability

- **“Process 33 has read-only access to vnode #5894”**
- **Records access rights for this process**
- **Quick verification on each read(), write()**
- **Result: per-process fd table “caches” results of ACL checks**

Internal Protection?

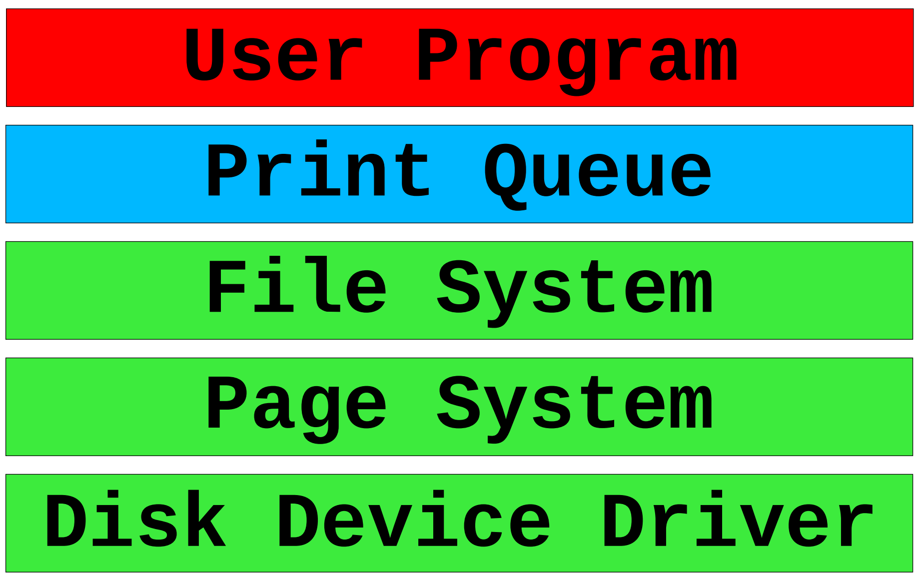
Understood so far:

- Which user process should be allowed to access what?
  - Job performed by OS
- How to protect OS code, data from user processes
  - Hardware user/kernel boundary

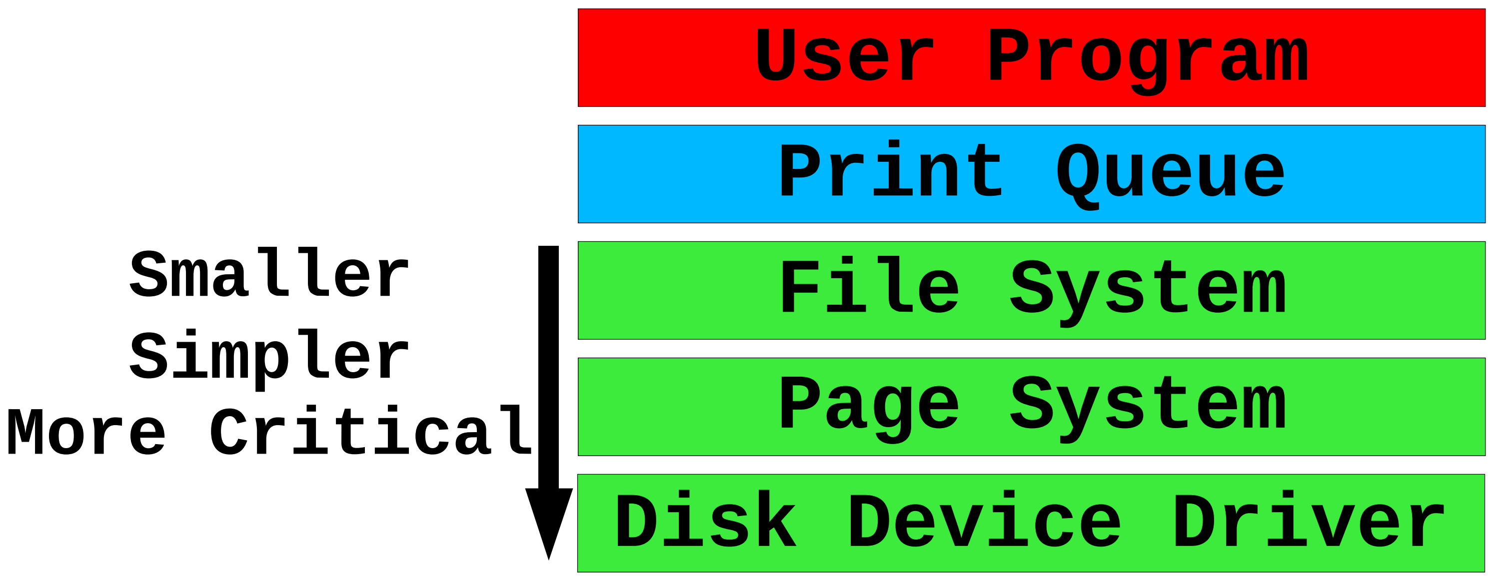
Can we do better?

- Can we protect *parts* of the OS from other parts?

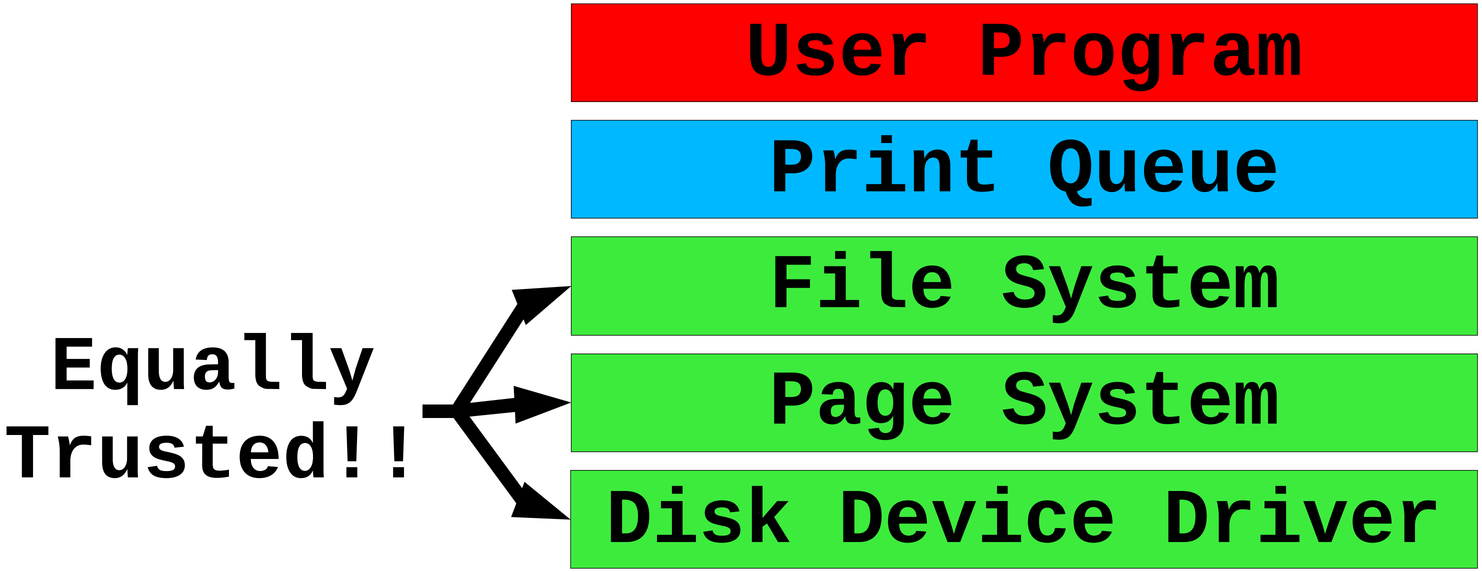
Traditional OS Layers



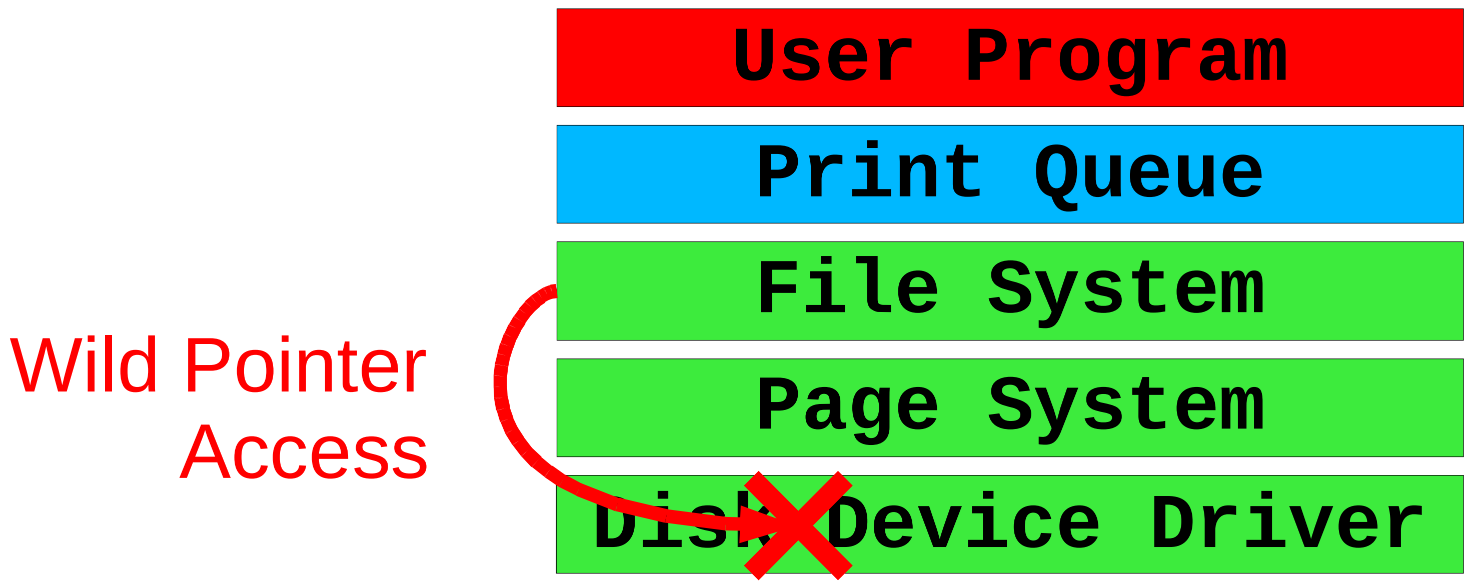
Traditional OS Layers



Traditional OS Layers



Traditional OS Layers



Multics

Multics =

- Multiplexed Information and Computing Service
- Plan: “information utility”
  - Mainframe per city

Designed to scale

- Many users, many programmers
- Protection seen as a key ingredient of reliability

Multics Approach

Trust *hierarchy*

Small "simple" very-trusted *kernel*

- **Main job: access control**
- **Goal: "prove" it correct**

Privilege layers (nested "rings")

- **Ring 0 = kernel, "inside" every other ring**
- **Ring 1 = operating system core**
- **Ring 2 = operating system services**
- **...**
- **Ring 7 = user programs**

Multics Ring Architecture

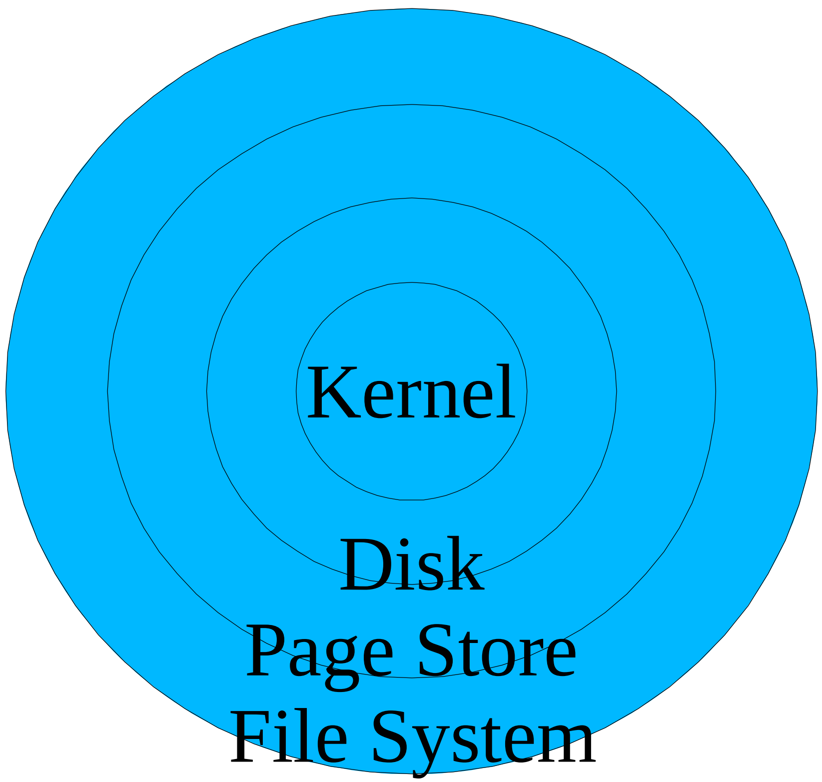
Segmented virtual address space

- "Print module" may contain
  - Entry points in a code segment
    - » `list_printers()`, `list_queue()`, `enqueue()`, ...
  - Data segment
    - » List of printers, accounting data, queues
- Segment ≡ file (segments persist across reboots)
- VM permissions focus on segments, not pages

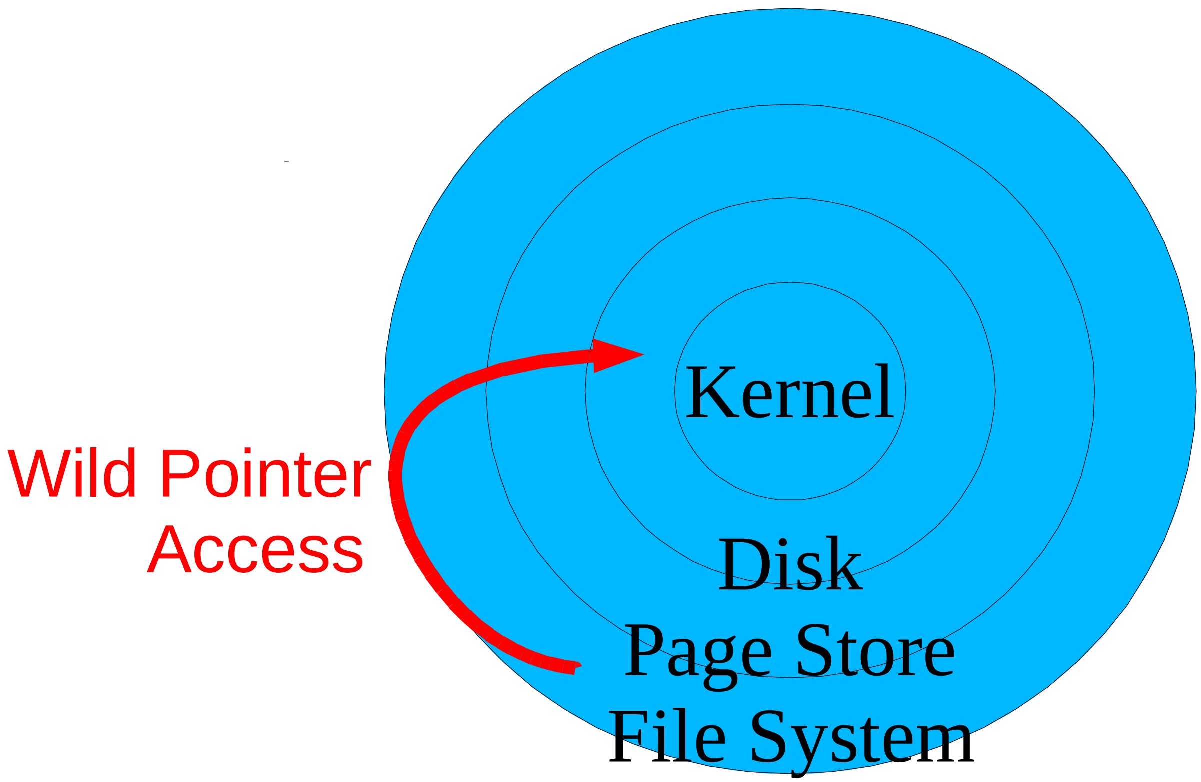
Access checked by hardware

- Which procedures can you call?
- Is access to that segment's data legal?

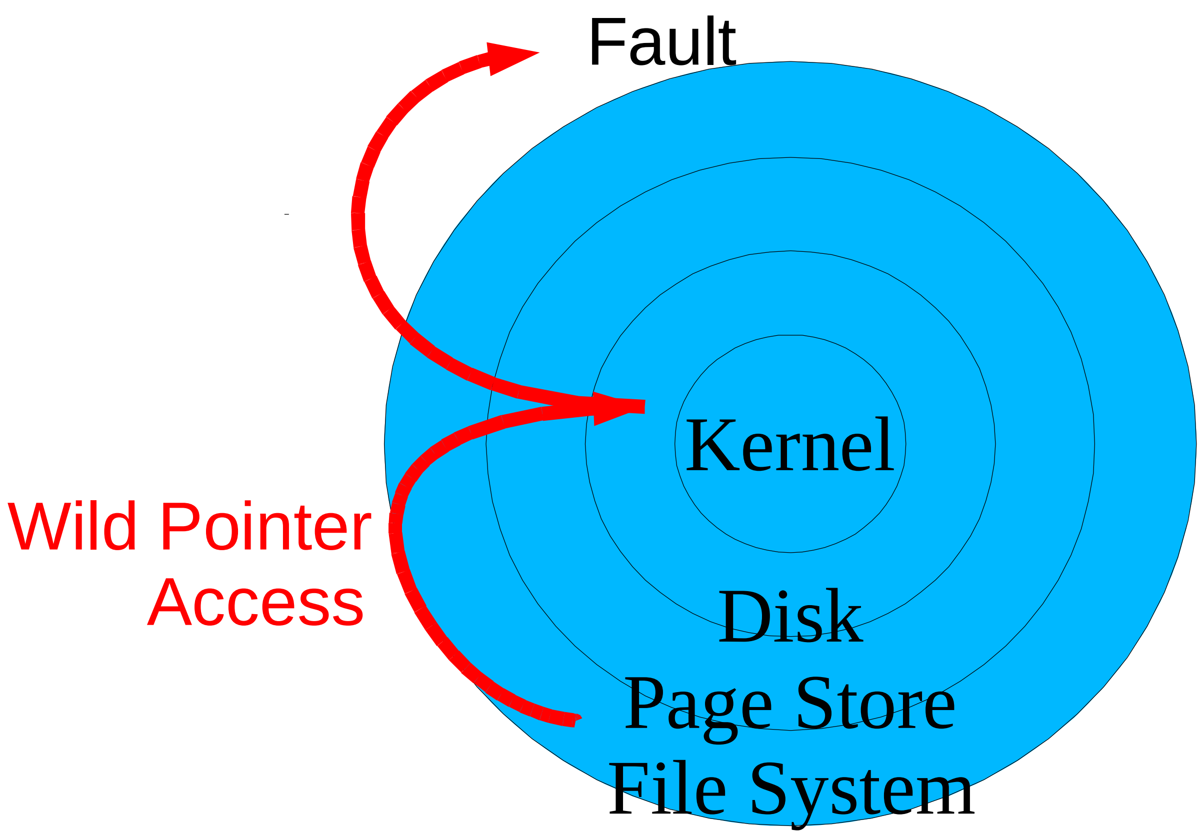
Multics Rings



Multics Rings



Multics Rings



Multics Domain Switching

CPU has *current ring number* register

- Current privilege level, [0..7]

Segment descriptors include

- “Traditional stuff”
  - Segment's limit (size)
  - Segment's base in physical memory
- Ring number
- Access bracket [min, max]
  - Segment “appears in” ring min...ring max
- Access bits (read, write, execute)
- Entry limit - “you must be this tall to access this segment”
- List of gates (procedure entry points)

Multics Domain Switching

Every procedure call is a potential domain switch

Calling a procedure at current privilege level?

- **Just call it**

Calling a more-privileged procedure?

- **Call mechanism checks entry point is legal**
- **We enter more-privileged mode**
- **Called procedure can read & write all of our data**

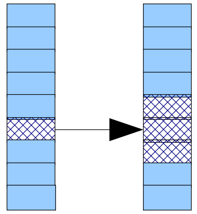
Calling a less-privileged procedure?

- **We want to show it *some* of our data (procedure params)**
- **We don't want it to *modify* our data**

Multics Domain Switching

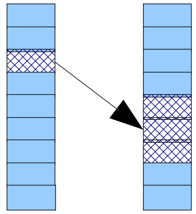
min <= current-ring <= max

- We are executing in ring 3
- Procedure is "part of" rings 2..4
- Standard procedure call



Multics Domain Switching

current-ring > max

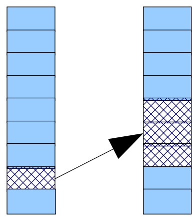


- Calling a more-privileged procedure
- It can do whatever it wants to us

Implementation

- Hardware traps to ring 0 permission-management kernel
- Ring 0 checks current-ring < entry-limit
  - User code may be forbidden to call ring 0 directly
- Checks call address is a legal entry point
  - Less-privileged code can't jump into middle of a procedure
- Sets current-ring to segment-ring
  - Privilege elevation – after consulting callee's rules
- Runs procedure call

Multics Domain Switching



current-ring < min

- **Calling a less-privileged procedure**

Implementation

- **Trap to ring 0 permission-management kernel**
- **Ring 0 copies "privileged" procedure call parameters**
  - **Must be in low-privilege segment for callee to access**
- **Sets current-ring to segment-ring**
  - **Privilege lowering – callee gets r/o access to carefully chosen privileged state**
- **Runs procedure call**

Multics Ring Architecture

Does this look familiar?

- It should really remind you of something...

Benefits

- Core security policy small, centralized
- Damage limited vs. Unix “superuser”' model

Concerns

- *Hierarchy* ≠ *least privilege*
- Requires specific hardware
- Performance (maybe)

More About Multics

Back to the future

- Symmetric multiprocessing
- Hierarchical file system (access control lists)
- Memory-mapped files
- Hot-pluggable CPUs, memory, disks
- 1969!!!

Significant influence on Unix

- Ken Thompson was a Multics contributor

The One True OS

- In use 1968-2000
- www.multicians.org

Mentioning EROS

Text mentions Hydra, CAP

- Late 70's, early 80's
- Dead

EROS (“Extremely Reliable Operating System”)

- UPenn, Johns Hopkins
- Based on commercial GNOSIS/KeyKOS OS
- www.eros-os.org
- “Arguably less dead” (see below)

EROS Overview

“Pure capability” system

- **“ACLs considered harmful”**

“Pure principle system”

- **Don't compromise principle for performance**

Aggressive performance goal

- **Domain switch ~100X procedure call**

Unusual approach to capability-bootstrap problem

- ***Persistent processes!***

Persistent Processes??

No such thing as reboot

Processes last "forever" (until exit)

OS kernel checkpoints system state to disk

- **Memory & registers defined as *cache of disk state***

Restart restores system state into hardware

"Login" *reconnects* you to your processes

EROS Objects

Disk pages
- capabilities: read/write, read-only

Capability nodes
- Arrays of capabilities

Numbers
- Protected capability ranges
  - “Disk pages 0...16384”

Process – executable node

EROS Revocation Stance

Really **revoking access is hard**

- **The user could have copied the file**

Don't give out real capabilities

- **Give out proxy capabilities**
- **Then revoke however you wish**

Verdict

- **Not really satisfying**
- **Unclear there is a better answer**
  - **Palladium/"trusted computing" isn't clearly better**

EROS Quick Start

http://www.eros-os.org/

- essays/
  - reliability/paper.html
  - capintro.html
  - wherefrom.html
  - ACLSvCaps.html

Current status

- EROS code base transitioned to CapROS.org
- Follow-on research project at Coyotos.org

Concept Summary

Object

- Operations

Domain

- Switching

Capabilities

- Revoking is hard, see text

“Protection” vs. “security”

- Protection is what our sysadmin *hopes* is happening...

Further reading?

- PLASH - “principle of least authority” shell for Linux