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Faculty of Computer Science Institute of Systems Architecture, Operating Systems Group

SOFTWARE SANDBOXES

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Outline

- Why and what to isolate?
- Machine-Level Isolation
  - Virtual Machines
  - OS-level isolation: chroot, BSD Jails, OS Containers, SELinux
- Application-Level Isolation
  - Chromium Architecture
  - Native Client

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The Need for Isolation

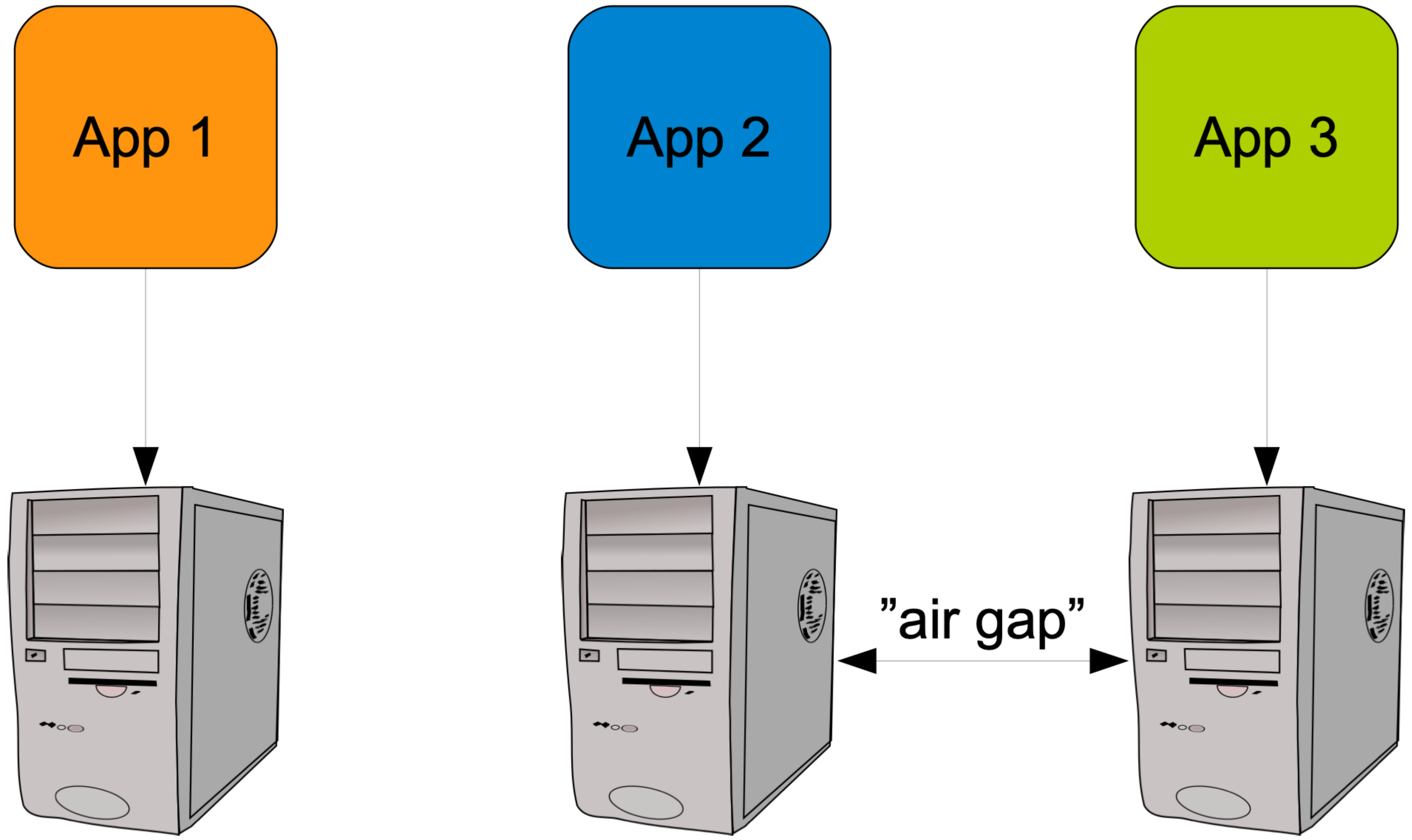
- Large-scale: Multi-user systems
  - Security:
    Prevent other users from reading/modifying my data...
  - Sharing:
    … but allow this for certain exceptions.
  - Fair distribution of resources (CPU time / network bandwidth) among users

- Small-scale: Integrate software from differing sources
  - Web browser: websites, plugins

Types of Isolation

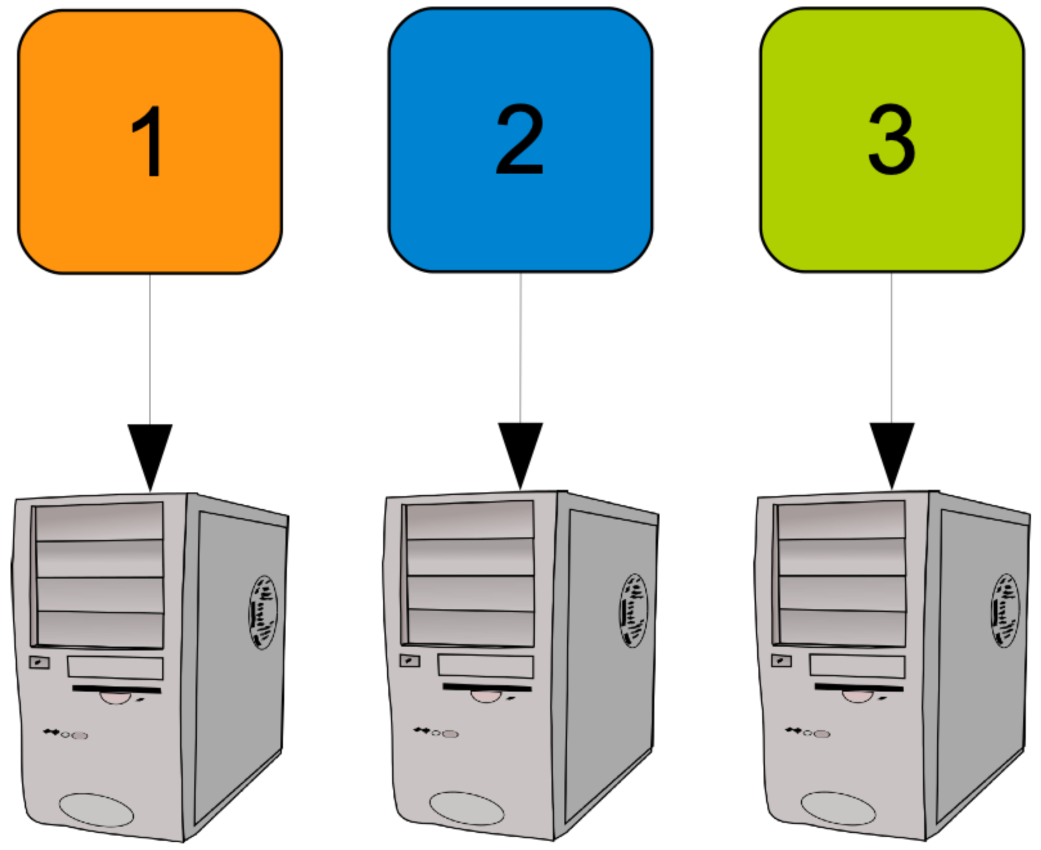
- **Fault Isolation**
  - A faulting application shall not take down others.
- **Resource Isolation**
  - Global resources shall be distributed fairly across all users
  - What is fair?
- **Security Isolation**
  - Applications shall not access or modify others' data.

Physical Separation



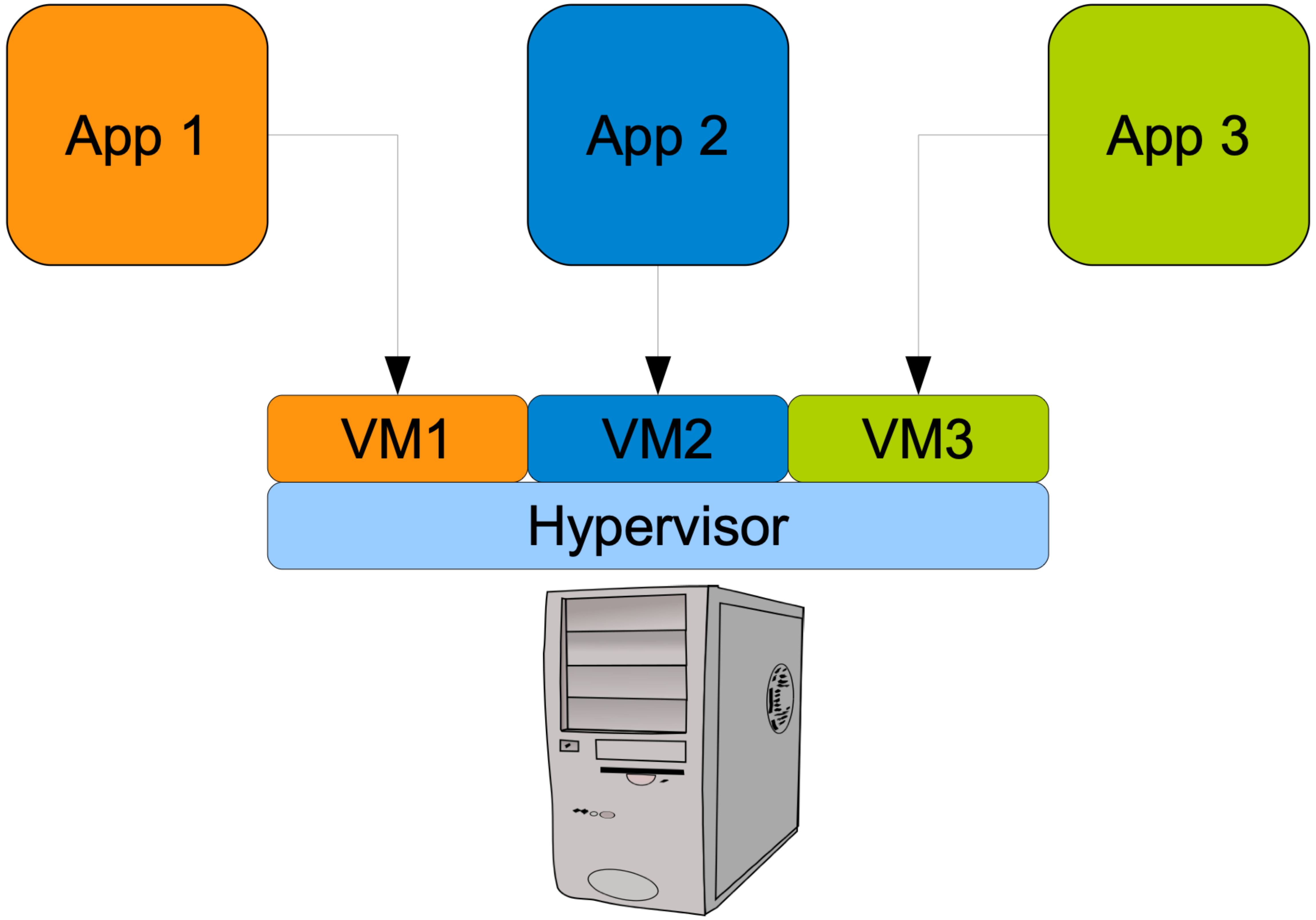
Physical Separation

- Advantages:
  - Achieves isolation
  - Different OS/software setups
- Disadvantages:
  - Resource overcommit
  - Administration effort
  - Sharing difficult



Virtual Machines

- Idea: better resource utilization by running multiple virtual machines on a single physical



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Virtual Machine Monitor

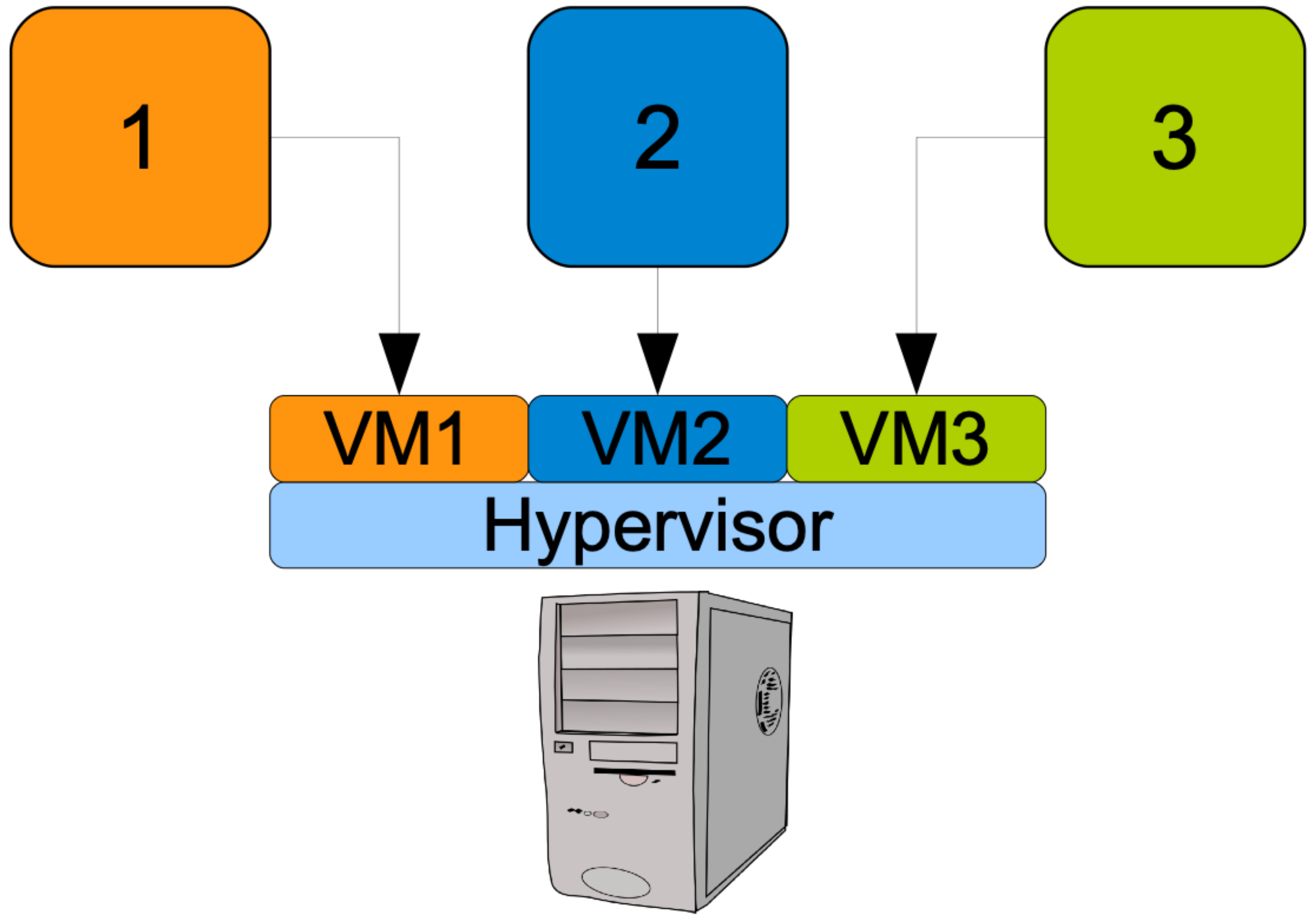
- Provides virtual hardware environment
  - Guest OS runs as on real hardware
  - Intercept (and emulate) privileged instructions
  - Virtual devices

- Type 1 – Bare metal
  - Runs as OS directly on hardware
  - e.g., VMware ESXi, Xen

- Type 2 – hosted
  - Part of a native OS (e.g., kernel module)
  - e.g., KVM, VirtualBox

Isolation with VMs

- Advantages
  - Isolation
  - Better resource utilization
  - Different OS/SW setups
- Disadvantages
  - Management
  - Slight Performance overhead
  - Sharing still difficult



Many more implementation issues: See lectures on **Microkernel-Based Operating Systems** and **Microkernel Construction**

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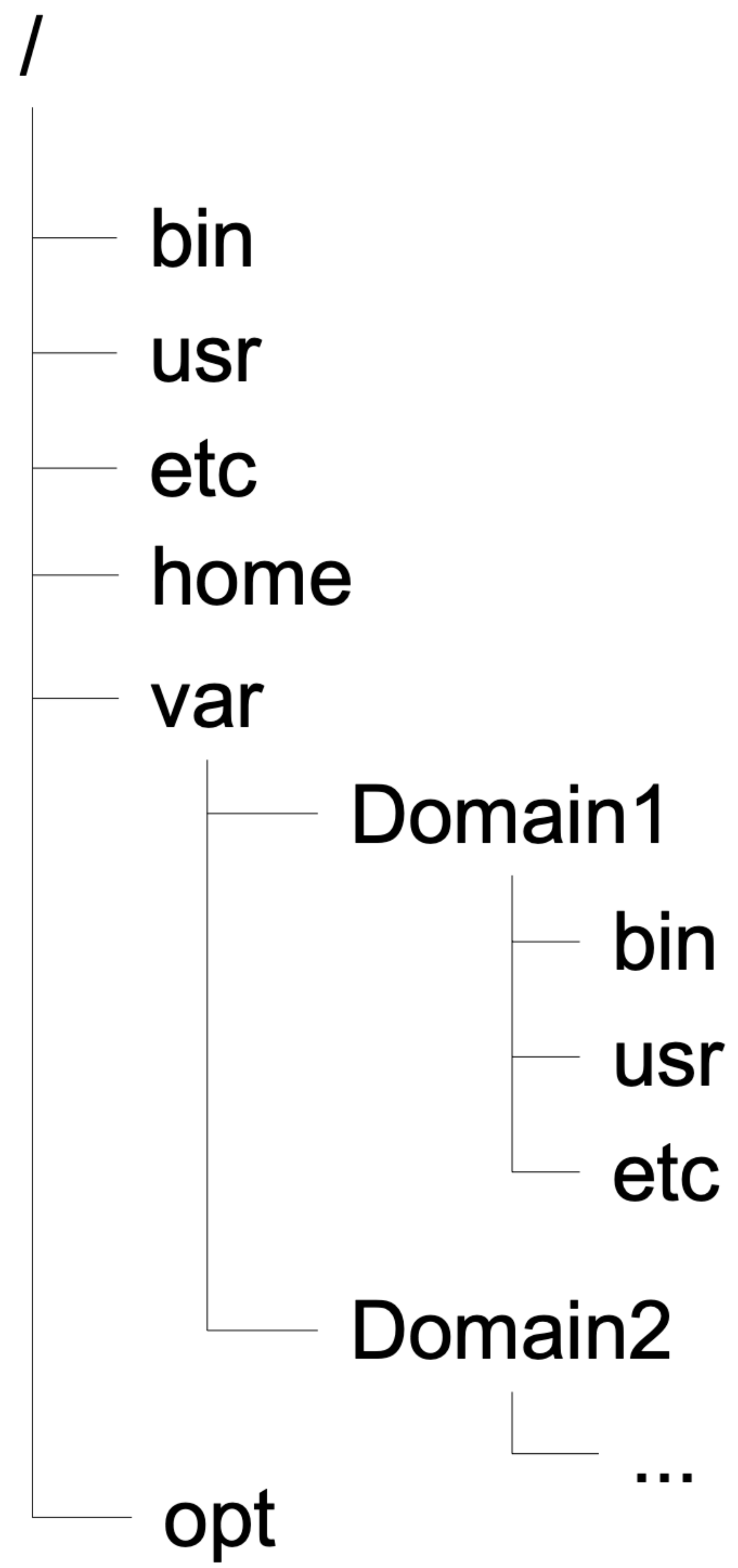
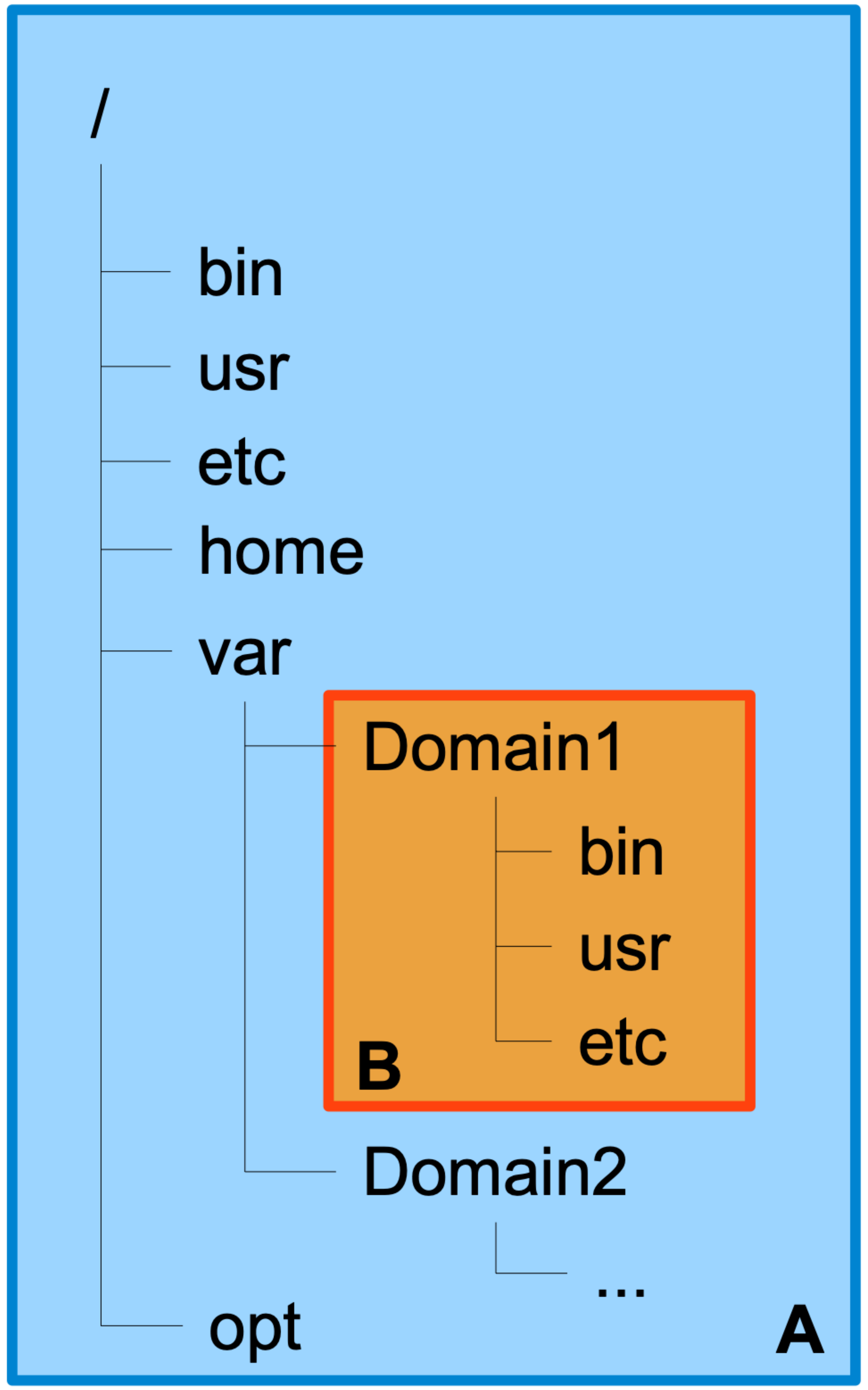
Multi-User System



- Unix path name resolution
  - Each process has a lookup root (default: /)
  - `open("/foo/bar/baz")` traverses file system hierarchy starting from this root
- (Limited) ACLs to manage access rights
  - Single group/owner not sufficient for complex access policies
- Idea: Restrict users/programs' access to parts of the file system → **chroot**

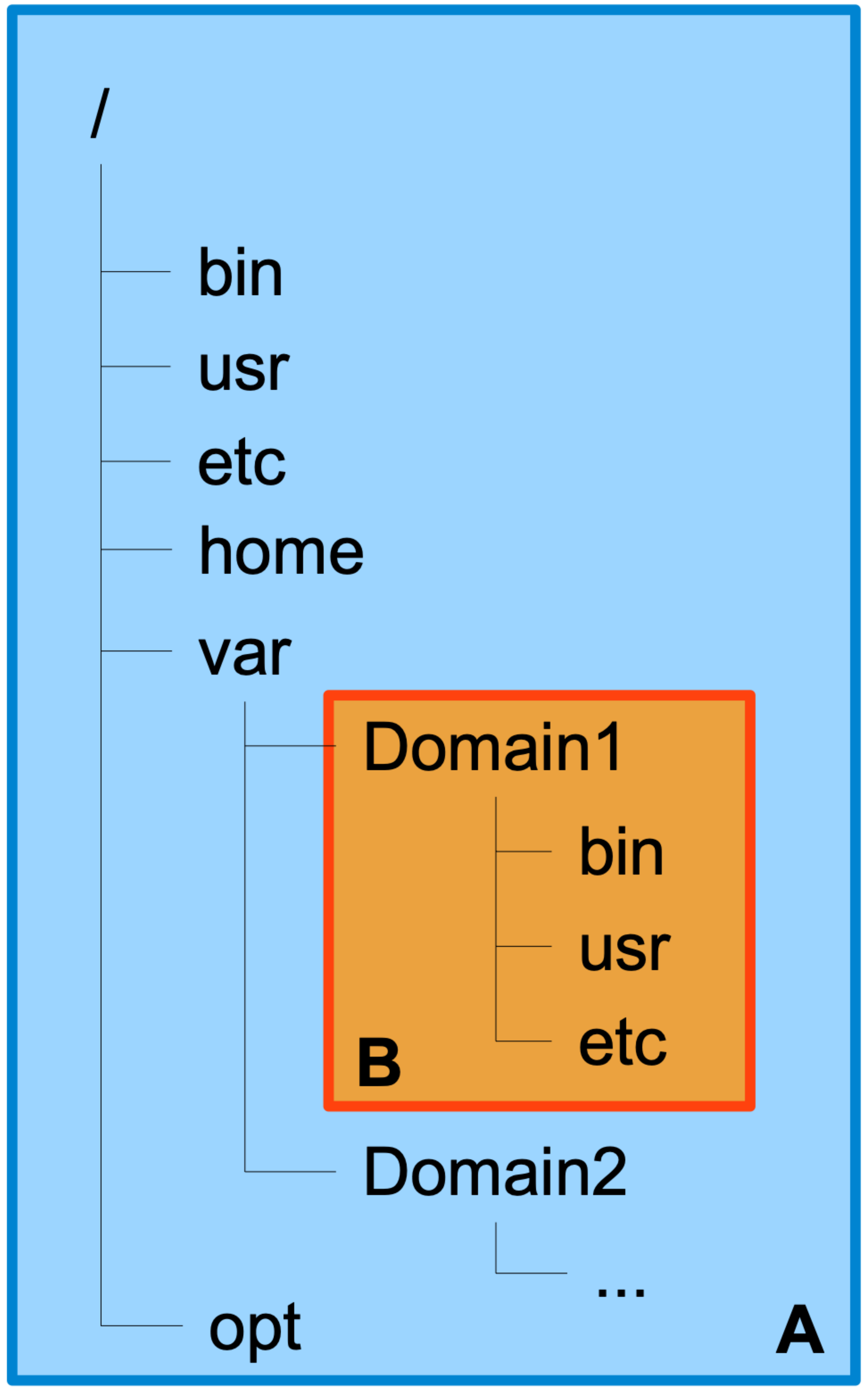
Chroot Example



- Process A:
  - Global file system access
  - `open("/bin/ls")` → returns file descriptor to `/bin/ls`
- A creates process B:

```
pid = fork();
if (pid == 0) // child
{
      chdir("/var/Domain1");
      chroot("/var/Domain1");
      setuid(some_user);
      execve("program B");
}
```

Chroot Example



- Process B now has /var/Domain1 set as its lookup root
  - `open("/bin/ls")` returns file descriptor to `/var/Domain1/bin/ls`
- Ideally, no access to anything outside /var/Domain1 possible for process B
- Sharing between users:
  - Make files/directories visible in different locations (e.g. linking)

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Chroot is not Isolation

- Chroot is meant to restrict file access of well-behaving applications
  - Intended for software testing

- No restrictions on
  - Loading kernel modules
  - Opening network connections
  - Reading `/dev/kmem`
  - Tracking other processes (e.g., through `ps` / `top`)

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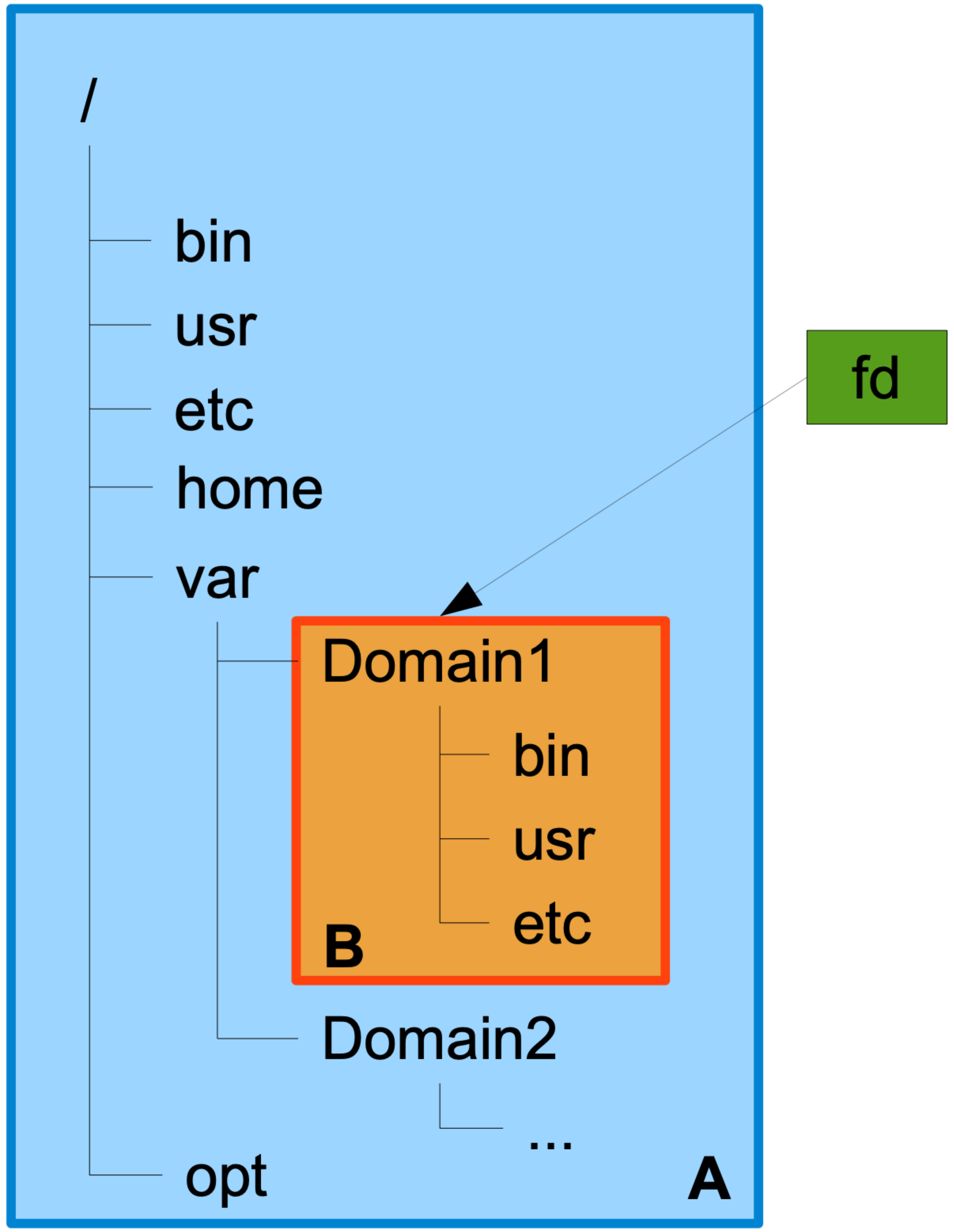
Breaking out of chroot

- Step 1: Become root
  - Find an exploit as described in last week's lecture

- Step 2:

```
fd = open(".", O_RDWR);
mkdir("./tmpdir", 0755);
chroot("./tmpdir");
fchdir(fd);
for (i = 0; i < 1024; ++i)
chdir("..");
chroot(".");
```

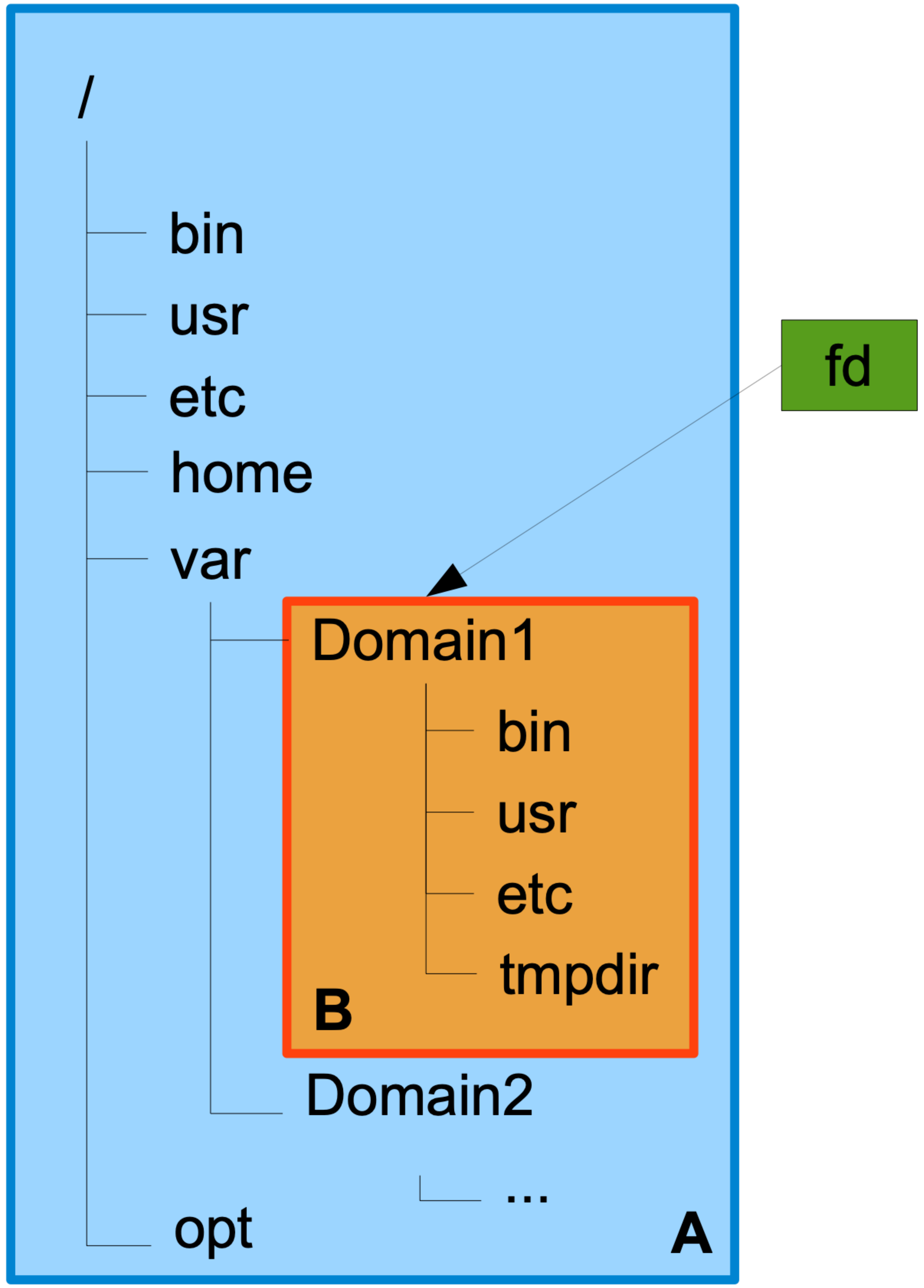
Breaking out of chroot



Starting as process B, `chroot'ed` to `/var/Domain1...`

`fd = fopen(".", O_RDWR);`
→ `fd` now contains valid file descriptor of `/var/Domain1`

Breaking out of chroot

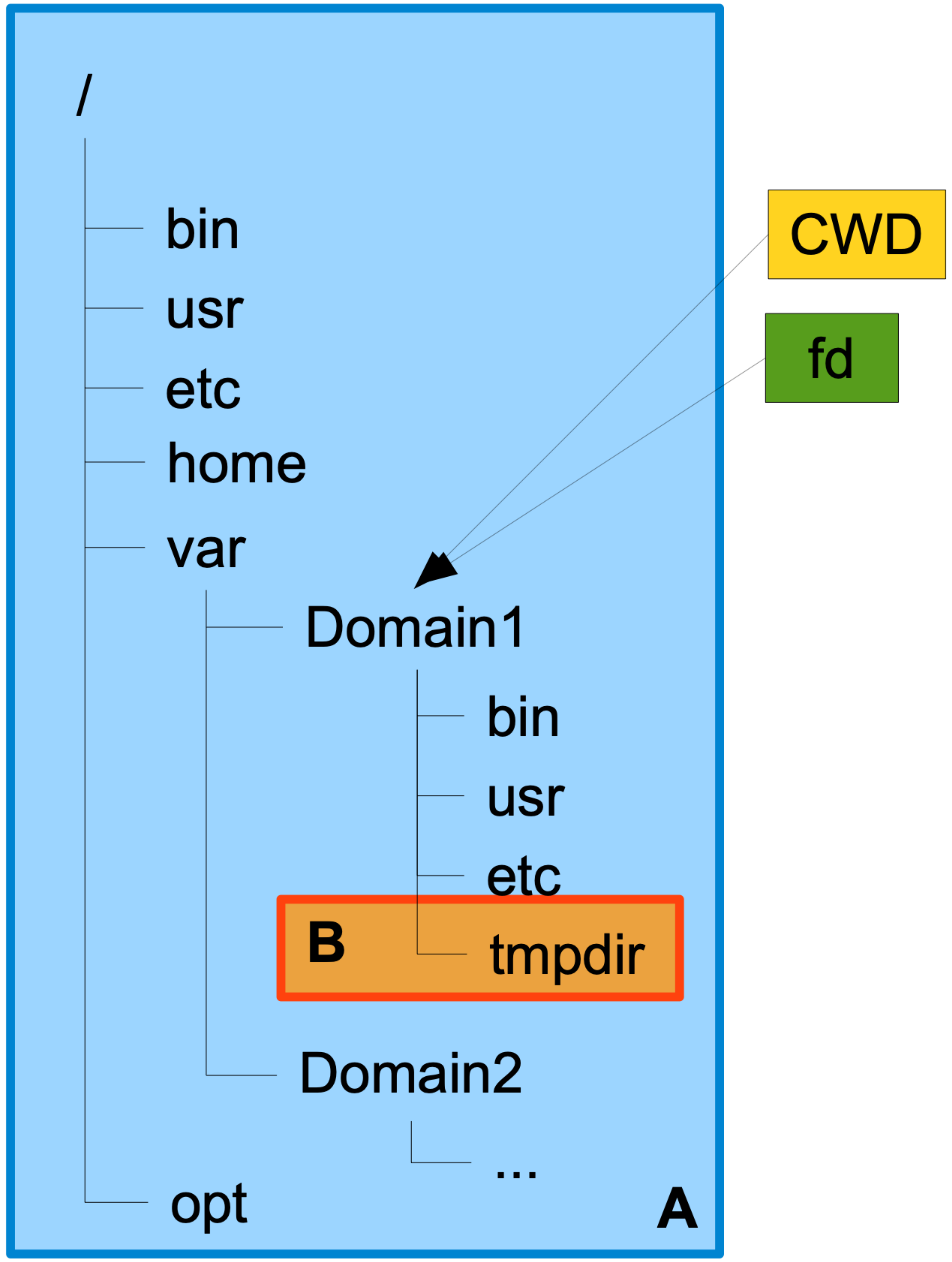


Starting as process B, `chroot'ed` to `/var/Domain1...`

`fd = fopen(".", O_RDWR);`
→ `fd` now contains valid file descriptor of `/var/Domain1`

`mkdir("./tmpdir", 0755);`
→ creates new directory 'tmpdir' below current one

Breaking out of chroot

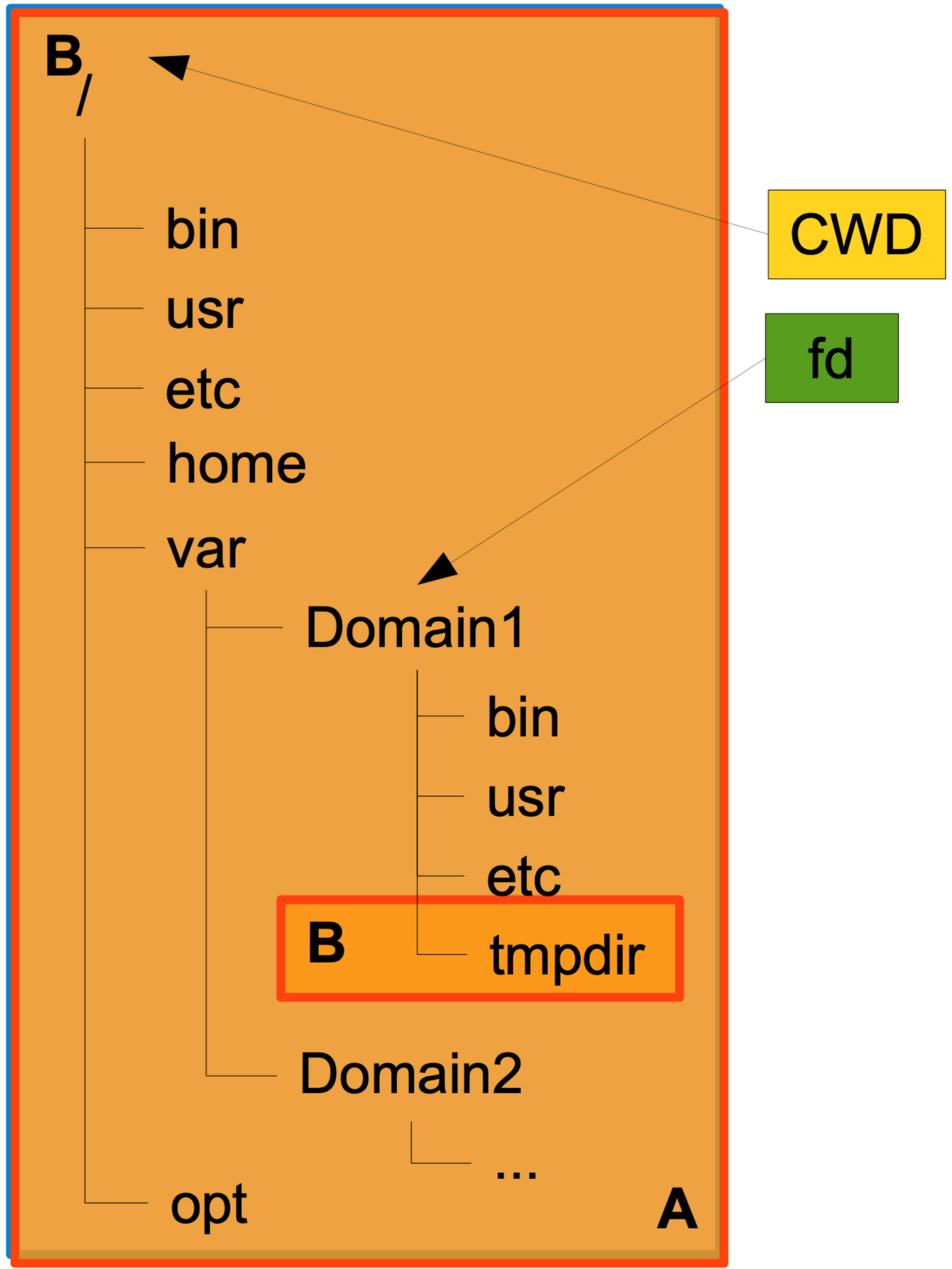


`chroot("./tmpdir")`
→ sets B's resolution root to `/var/Domain1/tmpdir`
→ so B can't access anything above, right?

But we still have a file descriptor pointing outside!

`fchdir(fd);`
→ sets the current working directory to `/var/Domain1`
→ this is POSIX-certified behavior

Breaking out of chroot



- Now `chdir("..")` in a long loop
- At some point we will hit the real root directory
- Now finally

  `chroot(".");`

  sets B's resolution root to /.
- Mission accomplished.

BSD Jails

- Based on chroot + kernel modifications

- Prohibited:
  - Loading kernel modules
  - Modify network configuration
  - (Un-)mount file systems
  - Create device nodes
  - Access kernel runtime parameters (sysctl)

- Permitted:
  - Run programs within jail (working directory...)
  - Signalling processes within a jail
  - Modification of in-jail file system
  - Bind sockets to TCP/UDP ports defined at jail creation

Jails Implementation

- Added `jail` system call
  - Create jail structure → unmodifiable after setup
  - Attached to every process
    - Only processes within a jail can add processes to it
    - No breaking out of `chroot`
- Adapted other system calls
  - Limit PID/GID/TID-based system calls
- Had to adjust some drivers
  - e.g., virtual terminal needs to belong to specific jails

Access Control Theory

- **Discretionary Access Control (DAC)**
  - Security (isolation) enforced based on object-subject relationship
  - Linux: File System → file ownership
- **Mandatory Access Control (MAC)**
  - Isolation based on object – (subject x operation) relationship
  - e.g., Program A with UID X may read a file;
Program B with UID X may also write it
  - Linux: File System ACLs (limited to 3 operations)
- **Role-Based Access Control (RBAC)**
  - Subjects can have dynamic roles assigned
  - Access based on object-role relationship
- ***Principle of Least Privilege***

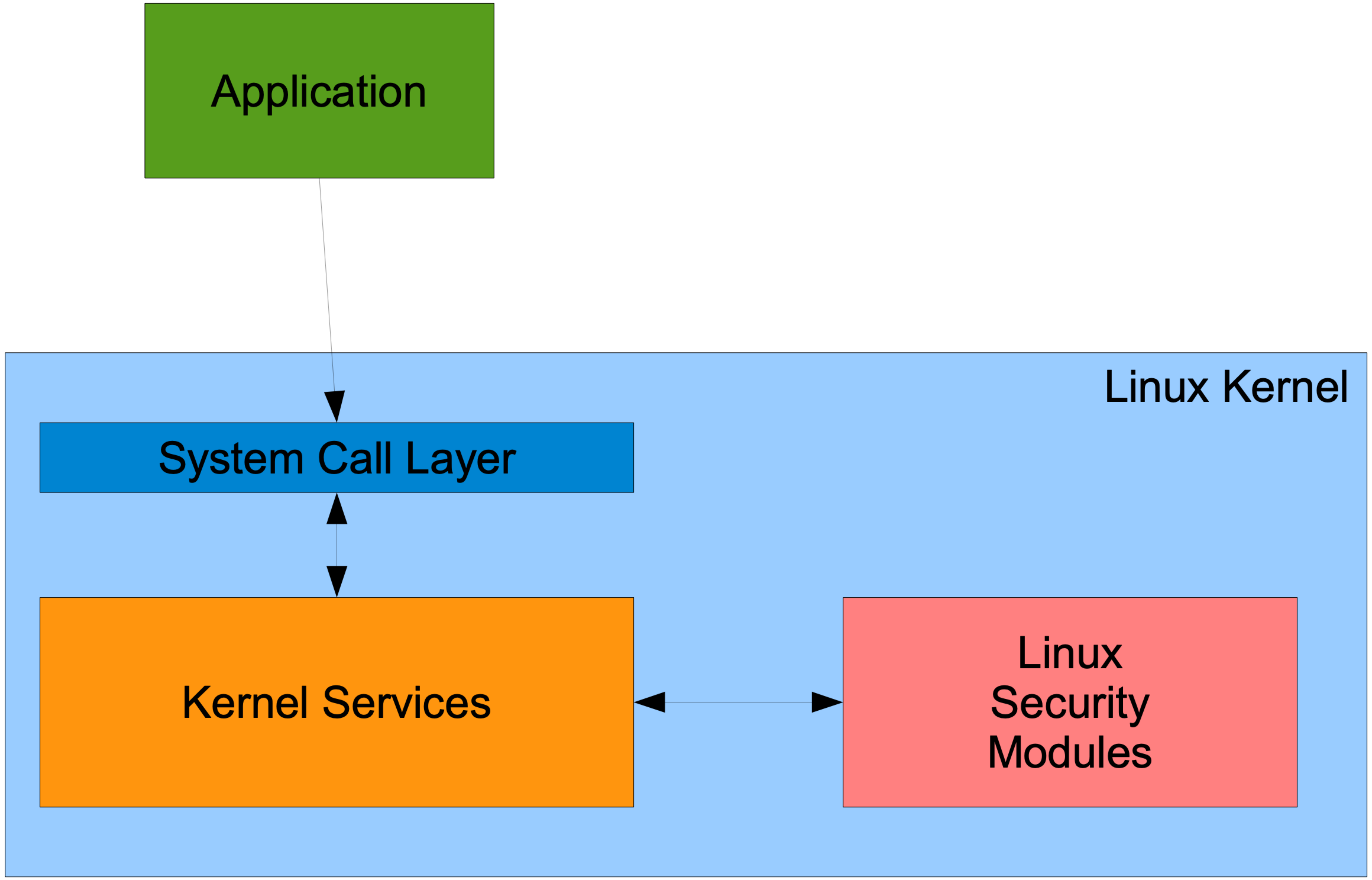
SELinux

- RBAC for Linux (co-developed by NSA...)
- Type Enforcement
  - Processes are placed in dedicated sandboxes (domains)
  - Fine-grained configuration per domain
    - Which files can be accessed? (And how?)
    - Which network ports can be bound to?
    - Can the app render to an X11 window?
    - Can the app fork() new processes? In which domain?

SELinux Policies

- Policy files define
  - User roles
    user `joe` → `role user_t`
  - Object types
    dir `/etc/selinux` → `policy_src_t`
  - Permissions
    `r_dir_file(user_t, policy_src_t)`
    → user_t may read policy_src_t
- `checkpolicy` compiler generates loadable kernel module to enforce rules

SELinux Architecture



LSM: Linux Security Modules

- Loadable Kernel Modules

-
```
struct security_operations {
    [..]
    int (*file_open) (struct file *,
                      const struct cred *);
    [..]
};
```

-
```
extern int register_security(
           struct security_operations*);
```

LSM Callback Hooks

```
static int do_entry_open(struct file *f, …,
                         const struct cred *cred)
{
    [...]

    error = security_file_open(f, cred);
    if (error) { … }

    [...]
}
```

Containers

- Jails, SELinux: security isolation + some fault isolation
  - Process cannot modify state outside its jail
  - Fine-grained SELinux policies may also limit fault propagation
    - But configuration is a mess...
- Resource isolation still missing
- Enter: container-based virtual machines
  - Recent gain in popularity:
    https://linuxcontainers.org
    http://www.docker.com

Containers

- Full virtualization is expensive
  - Implementation overhead
    - Need to have pass-through drivers available
  - Management overhead
    - VM configuration in addition to setup of guest OS
  - Runtime overhead (though small)

- Often we don't need all features
  - Many use cases warrant ”A Linux installation”

Linux VServer

- Jails-like Linux modification
  - Extended chroot
    - Chroot barrier: prevent breaking out
  - PID / resource name spaces + filtering
  - Network isolation
    - only bind apps to predefined set of IP addresses / ports

- Share libraries / kernel across VM instances

VServer: Resource Isolation

- Goal: Fair distribution of resources (e.g. CPU time)
- But what is fair?
  - Fair share → each VM gets the same amount of compute time
  - Proportional Share → VMs with more processes get larger amount of resources
- Linux: Completely Fair Scheduler (CFS)
  - All processes get the same amount of time
  - No notion of process-VM mappings

VServer: Token-Bucket Scheduler

- Each VM has a bucket
- Every timer tick removes a token from VM's bucket
- If bucket is empty: remove all VM's processes from run queue until threshold of tokens has been refilled
- Refill: over time according to some policy
- Allows to implement proportional and fair share

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VServer: I/O

- Network: use existing Linux traffic shaping mechanisms
  - Bandwidth reservations
  - Shares → specify how non-reserved bandwidth is distributed between VMs
- Disk: rely on Linux disk scheduler to do the right thing
  - Disk is less about isolation, more about optimizing accesses

Linux namespaces

- All modern container implementations based on Linux namespaces
- Virtualizes these resources:
  - Mount (mnt), process (pid), network (net)
  - Inter-process communication (ipc)
  - Host and domain names (UTS)
  - User IDs (user), Control group (cgroup), time
- Basis of Docker, LXC, Rkt, Singularity, …

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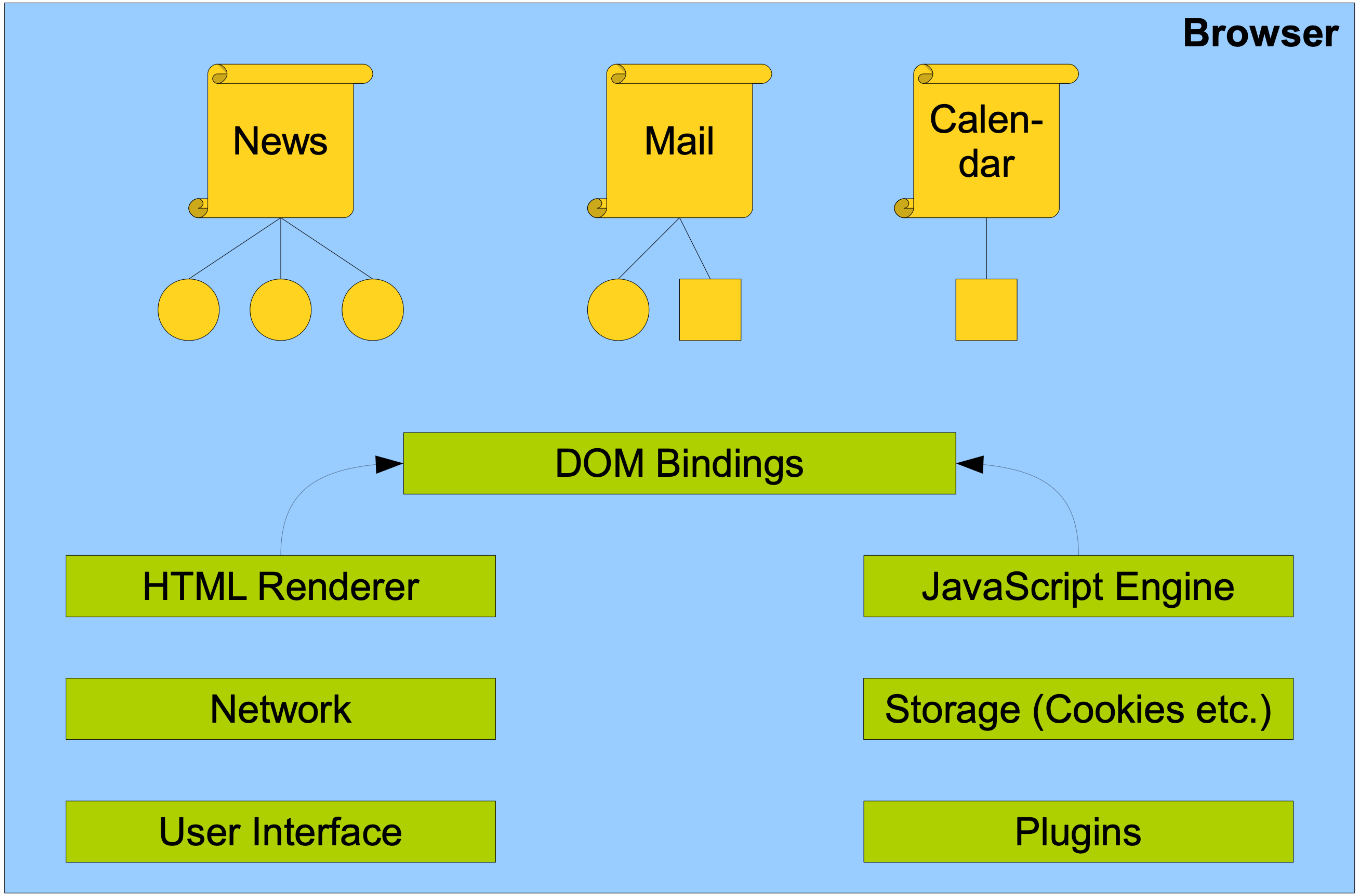
Application-level Isolation

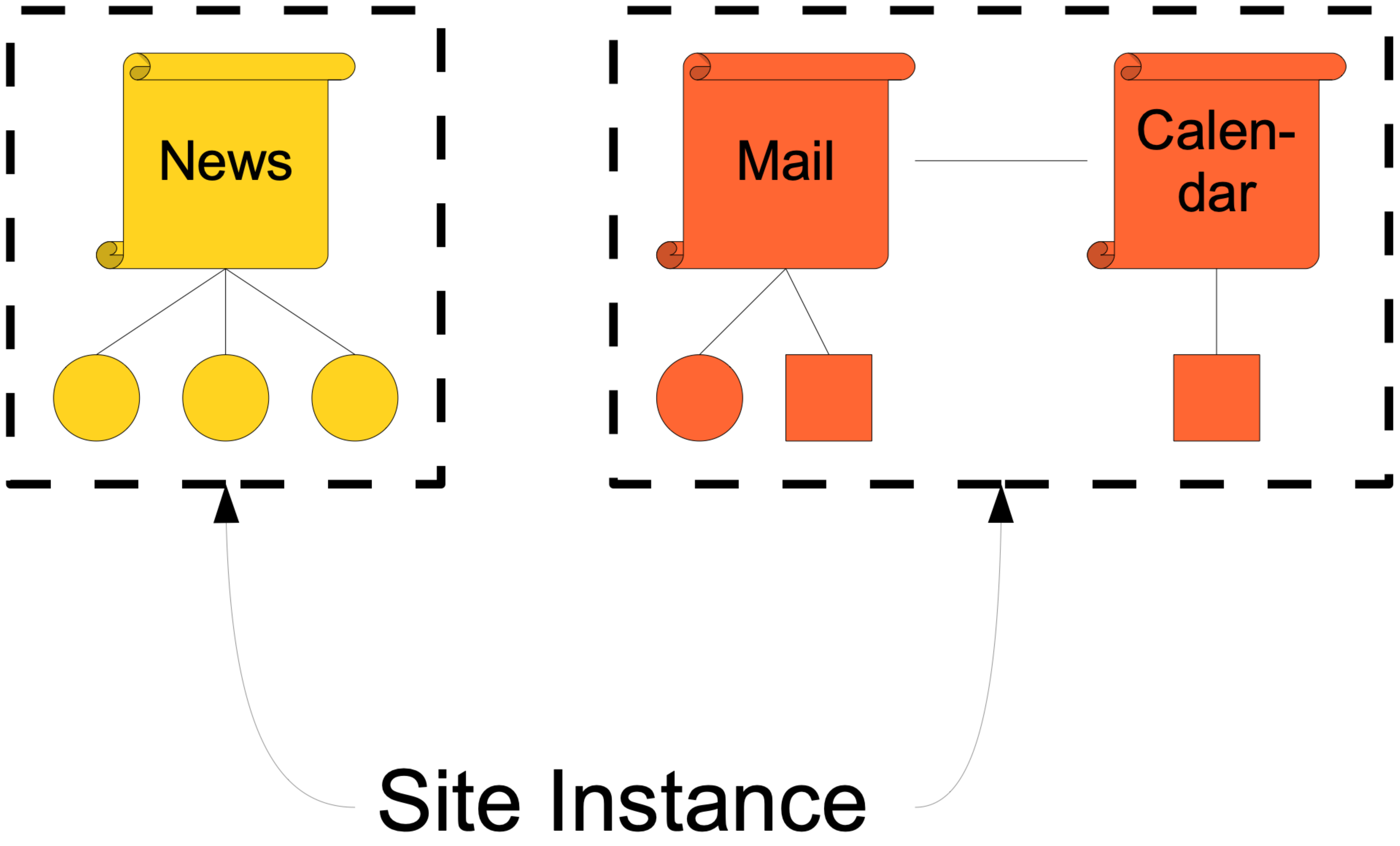
Web Browser, ca. 2008



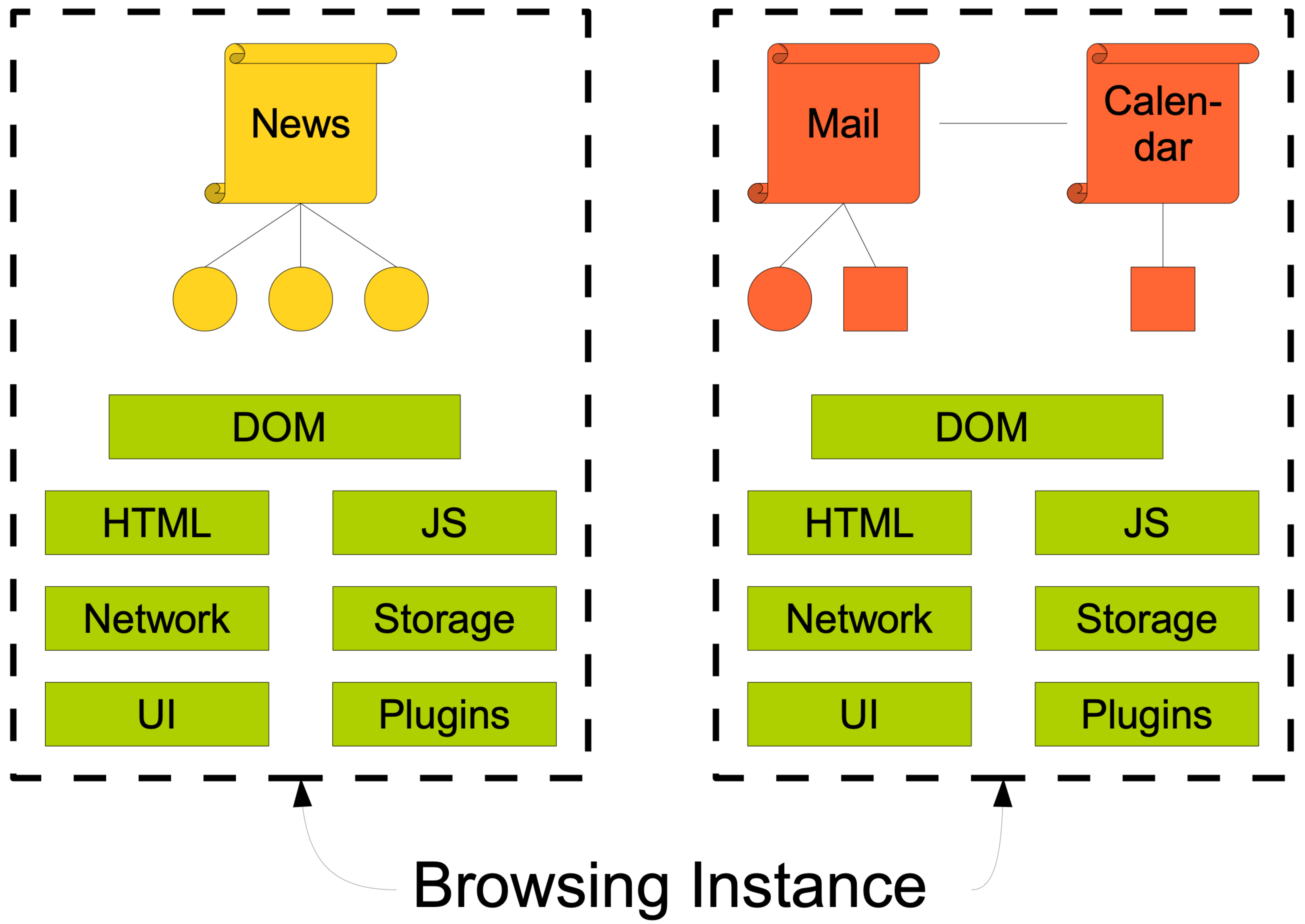
Monolithic Browsers

- Web pages communicate through DOM
  - Unrelated page can inspect and modify data
  - Access Control: Same-Origin Policy
    http://www.example.com
    http://www.example.com/p2
    https://www.example.com
- Web pages may include data from different sources (e.g., iframes)
- User credentials stored by browser
  - May be (mis-)used by other pages
- Per-page isolation infeasible: web apps need multiple pages
  - Calendar window
  - Email compose window
  - ...

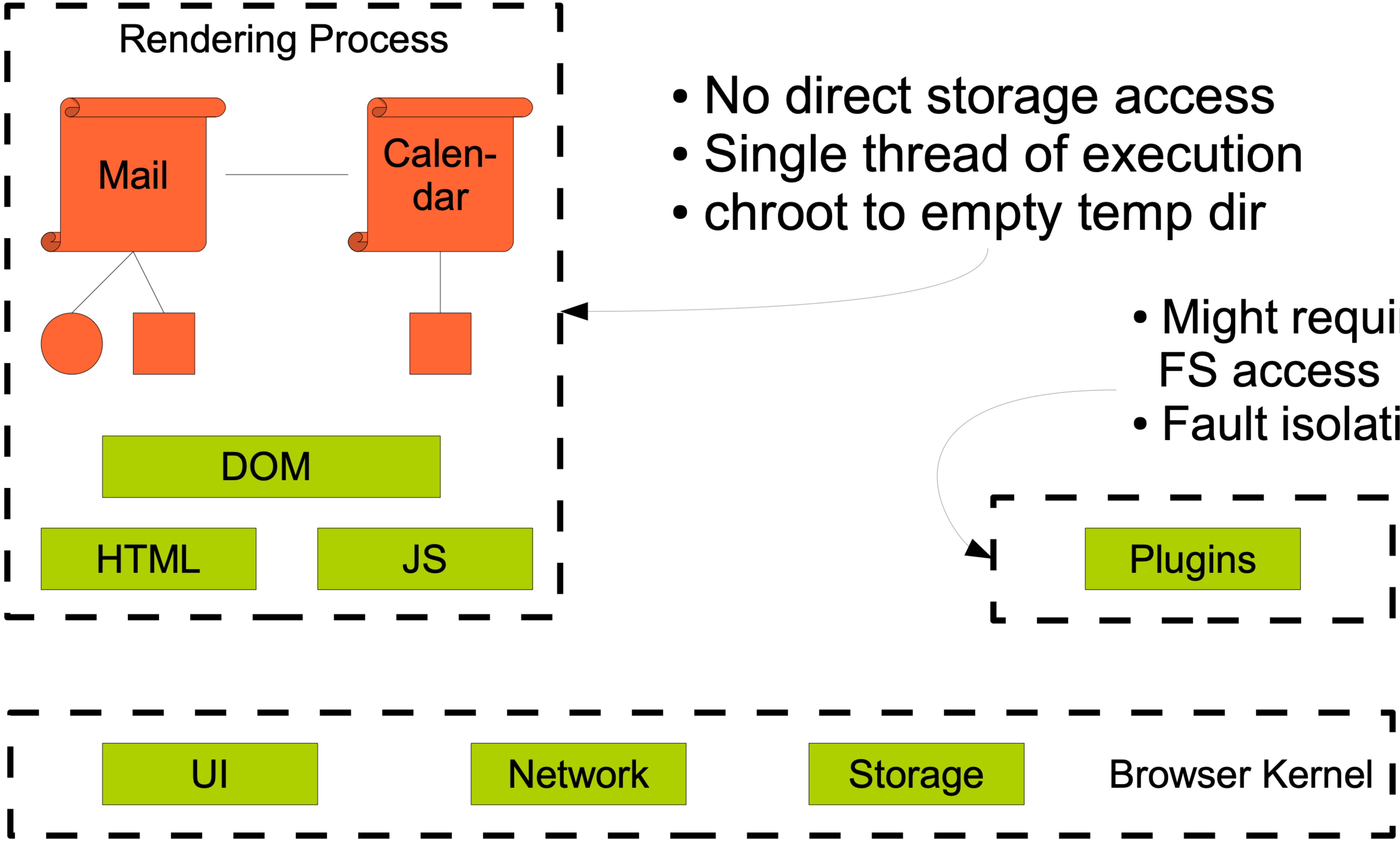
Chromium: Isolating Web Programs



Chromium: Isolating Web Programs



Web Processes



- No direct storage access
- Single thread of execution
- chroot to empty temp dir

- Might require FS access
- Fault isolation

Chromium & Co.

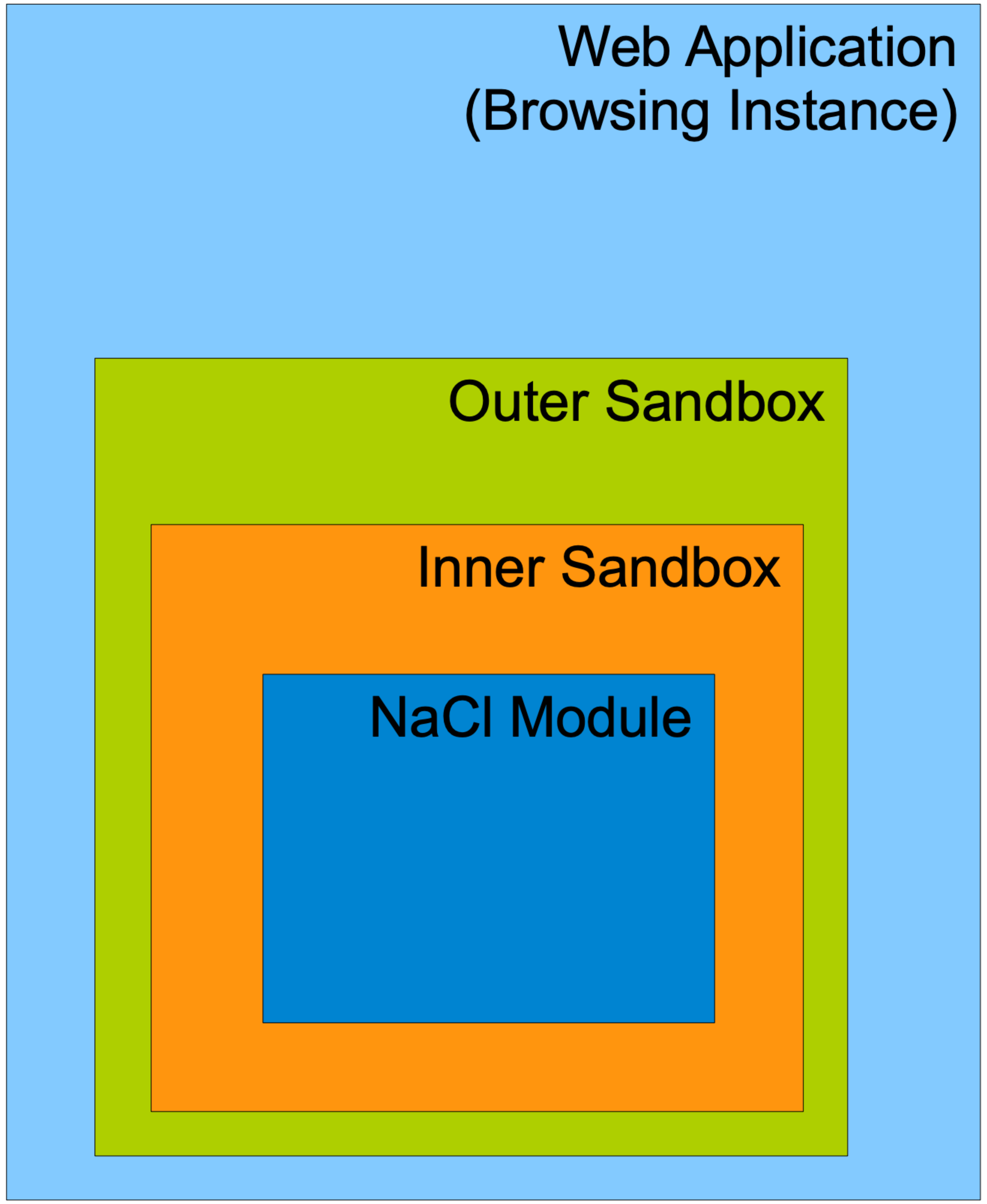
- Isolate web pages into OS processes
- Difficult:
  - determine exact boundaries...
  - … while maintaining compatibility
- Gain:
  - Security & Fault Isolation between web pages
  - Performance → parallel rendering possible
  - Accountability
- Enter unlimited possibilities of cloud wonderland...

Problems with Plugins

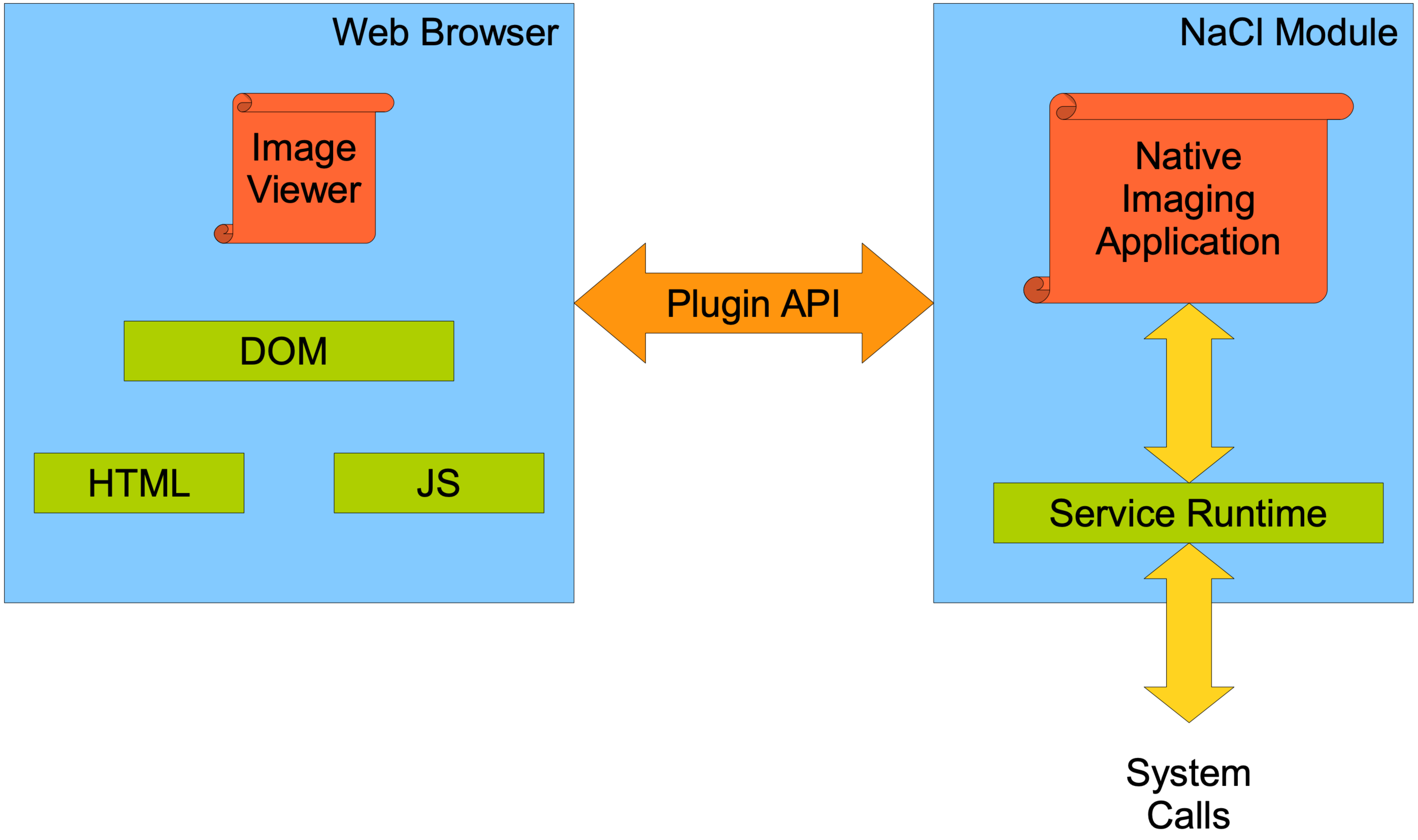
- Goals:
  - Native code execution (JIT or interpreted)
  - Access to local resources (disk, …)
- Problems:
  - Circumvent browsers' security mechanisms
  - Arbitrary code execution possible
- Solutions
  - Ask for user approval before running plugin
  - Language-level security (e.g. Java Class Loader) → often open up new attack surface
  - Process Isolation → protects web pages, can still exploit system call interface

Native Client (NaCL)

- Allow plugins (**NaCl modules**) compiled to native x86 code
- **Inner Sandbox**: limit execution to module's code and data
- **Outer Sandbox**: System Call Policy Enforcement (think: SELinux)



NaCL: App Model



NaCL Modules

- NaCl module and service runtime in same address space
  - Module code must not break out of its text/data region
  - But we need well-defined ways to
    - Perform system calls (if policy permits)
    - Communicate with web page through plugin API
- Solution: Dedicated compiler (adapted GCC) that enforces rules on NaCl modules

NaCL Module Rules

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- Once loaded, the binary is not writable
  - Enforced using mprotect()
  - Prevents self-modifying code

- Binary is statically linked
  (start address == 0, entry point = 64 kB)
  - No dynamically loaded code → allows static validation during startup
  - Predefined starting point required for load-time validation
  - Address restrictions: later

NaCL Module Rules

- All indirect control transfers use a nacljmp pseudo-instruction
  - Disable ret / function pointers → harden stack smashing

- The binary is padded up to the nearest page with at least one `hlt` instruction
  - Prevent jump to arbitrary address → will trigger `hlt`

NaCL Module Rules

- The binary contains no instructions or pseudo-instructions overlapping a 32-byte boundary
  - Alignment restrictions for indirect jumps (coming soon)
- All valid instruction addresses are reachable by disassembly that starts at the base address
  - Need access to all code for analysis
- All direct control transfers target valid instructions
  - Prevent jump into middle of instruction

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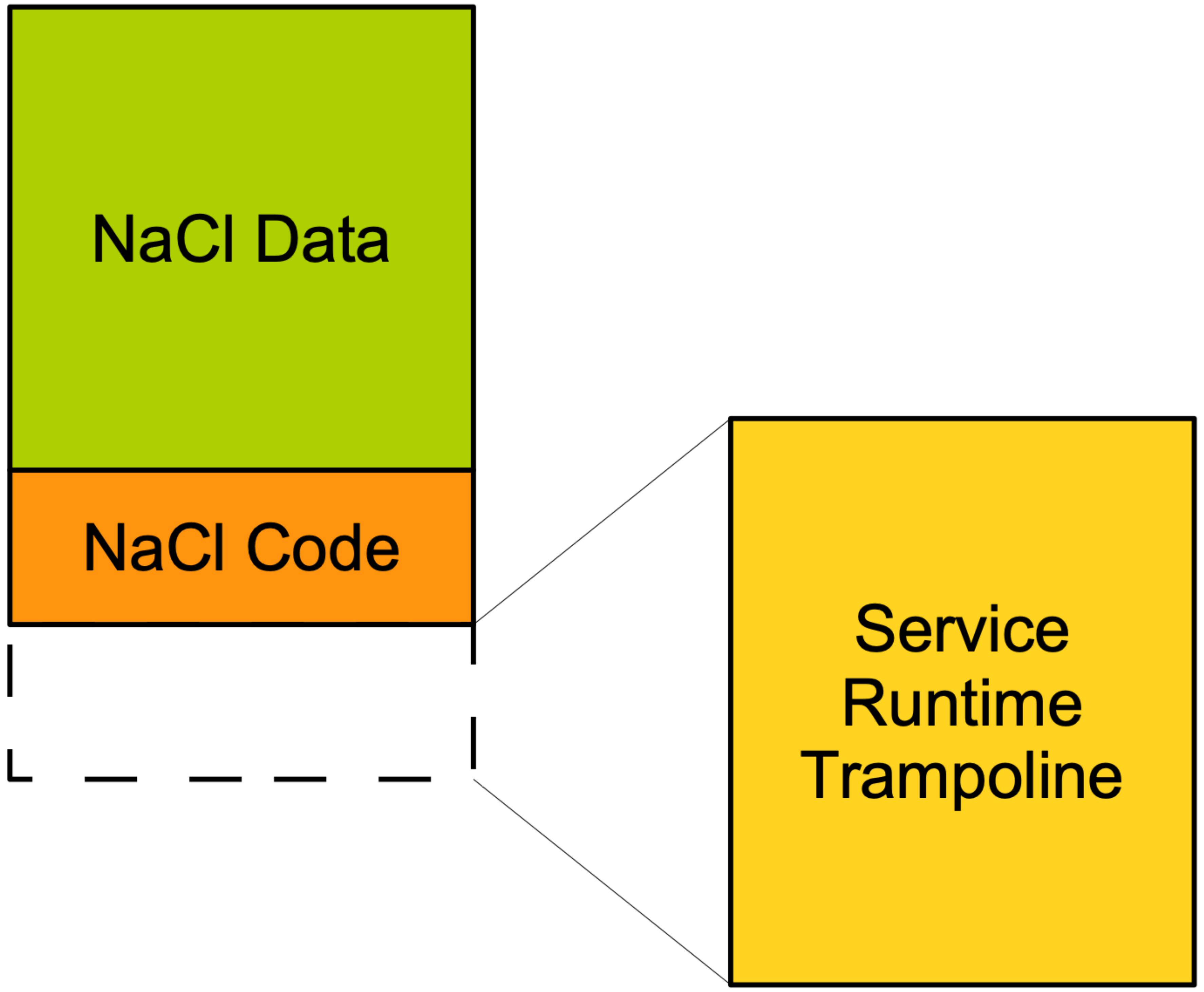
- Problem: x86 code may jump to arbitrary address (e.g., using `ret` or `jmp *%<register>`)
- NaCl: Alignment makes sure that every 32-byte aligned address is a valid instruction
- Use nacljmp instead of indirect control flow:

```
and   %<reg>, 0xFFFFFFE0
jmp   *%<reg>
```

- Result: code only contains jumps to valid targets
- Disallowed instructions
  - x86 segment modifications
  - `ret`
  - `syscall` / `int 0x*`
- No support for POSIX signals
  - They use the SS segment themselves
- Remaining issue: controlled calls into/out of the sandbox

NaCL Data Flow Integrity



- NaCl code may jump into trampoline (32-byte aligned)
- Each 32-byte aligned word is either
  - An entry to a service routine call
    - mmap / sbrk
    - thread creation
    - Plugin API calls
  - Or a HLT instruction
- Trampoline may contain unsafe code

NaCL Summary

- Plugins in isolated process
- Compiler enforces
  - Reliable Disassembly
- Sandbox enforces
  - Data Integrity
  - Control Flow Integrity
  - No unsafe instructions

Result: We can play Quake in the browser!

Update: Works with Javascript now, too!

Reading List

- Kamp, Watson: ***”Jails: Confining the omnipotent root”***, FreeBSD Tech Report, 2000
- Soltesz et al. ***”Container-based operating system virtualization: A scalable, high-performance alternative to hypervisors”***, EuroSys 2007
- Reis, Gribble ***”Isolating Web Programs in Modern Browser Architectures”***, EuroSys 2009
- Yee et al. ***”Native Client: A Sandbox for portable, untrusted x86 native code”***, IEEE Security & Privacy 2009
- Goldberg et al. **”A Secure Environment for Untrusted Helper Applications”**, Usenix SSYM 1996