Engineering Robust Server Software

UNIX Daemons

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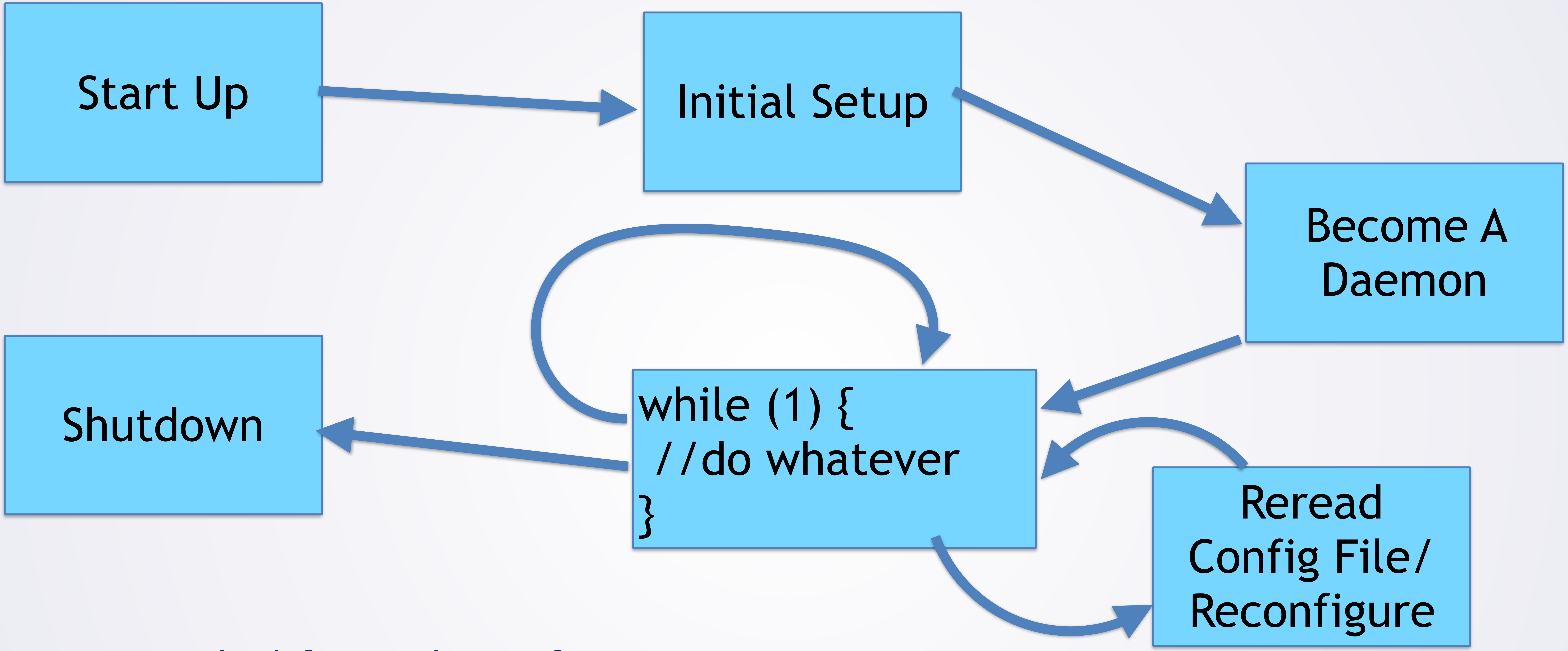
Andrew Hilton / Duke ECE

Daemons

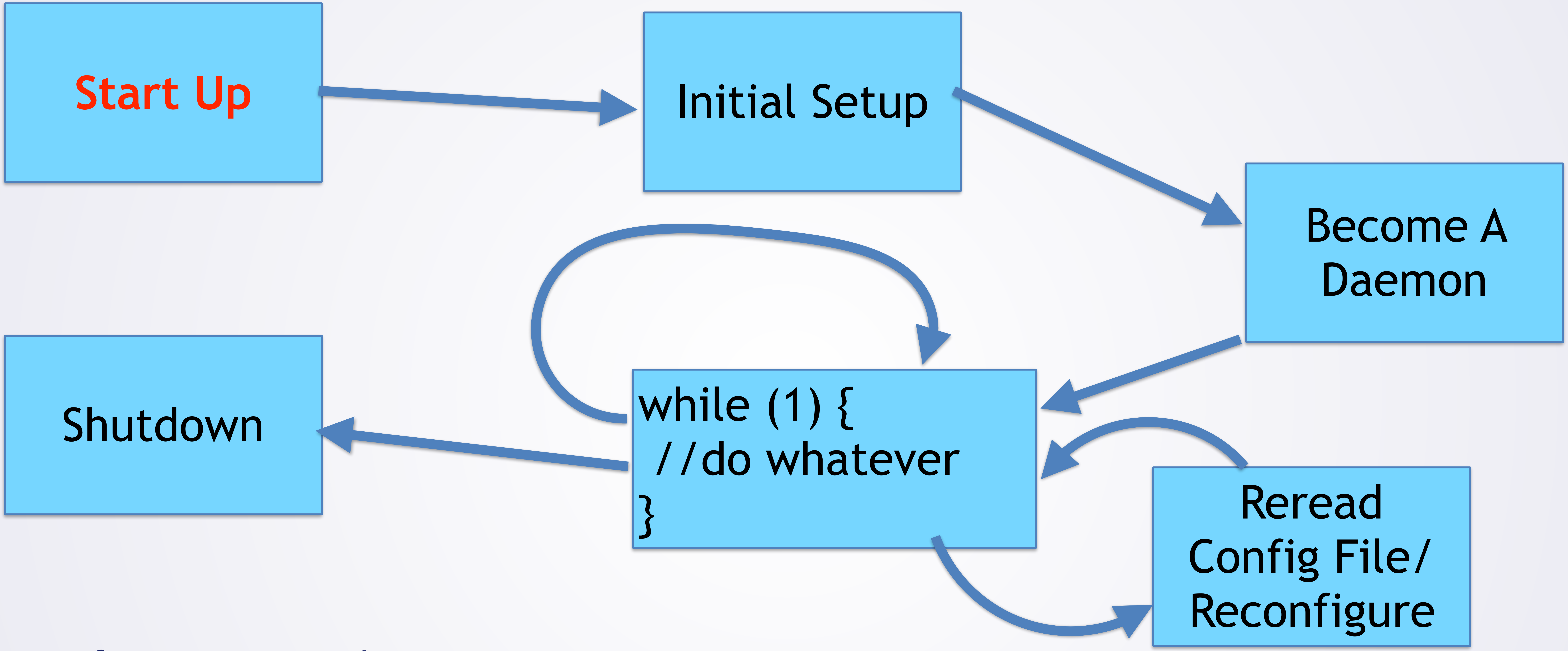
- Daemons: system services
  - Generally run startup -> shutdown
  - In the "background" no controlling tty
    - No stdin/stderr/stdout!
- Convention: names end in **d**
  - sshd, httpd, crond, ntpd, ….

Life Cycle



- General "life cycle" of a UNIX Daemon

Life Cycle



- Often: started at system startup
  - Could also be started manually

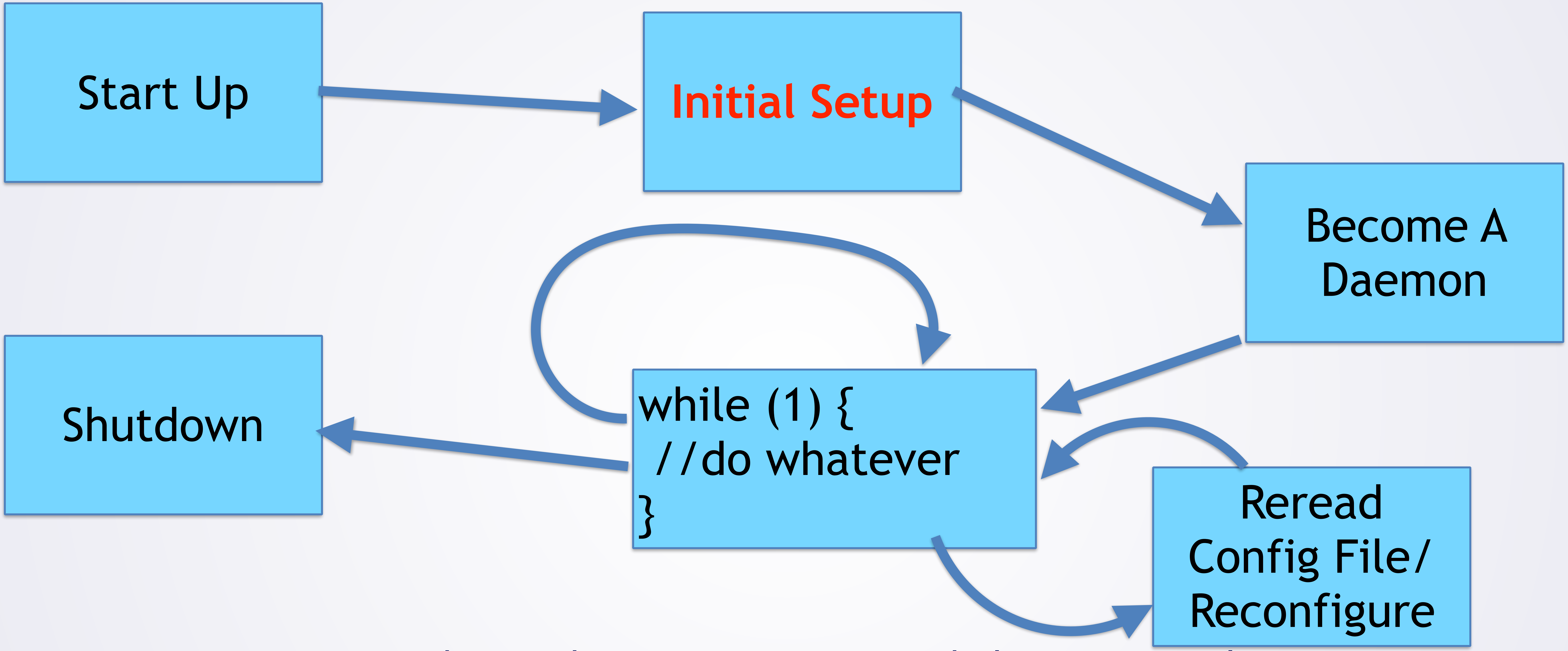
System Startup

- Review:
  - Kernel spawns init (pid 1)
  - Init (on Linux, now "systemd") spawns other processes
- Init itself is a daemon
  - Reads config, runs forever,…
- Init's config files specify how to start/restart/stop system daemons
- Details depend on specific version
  - E.g., systemd is different from original init

Init/Systemd Config

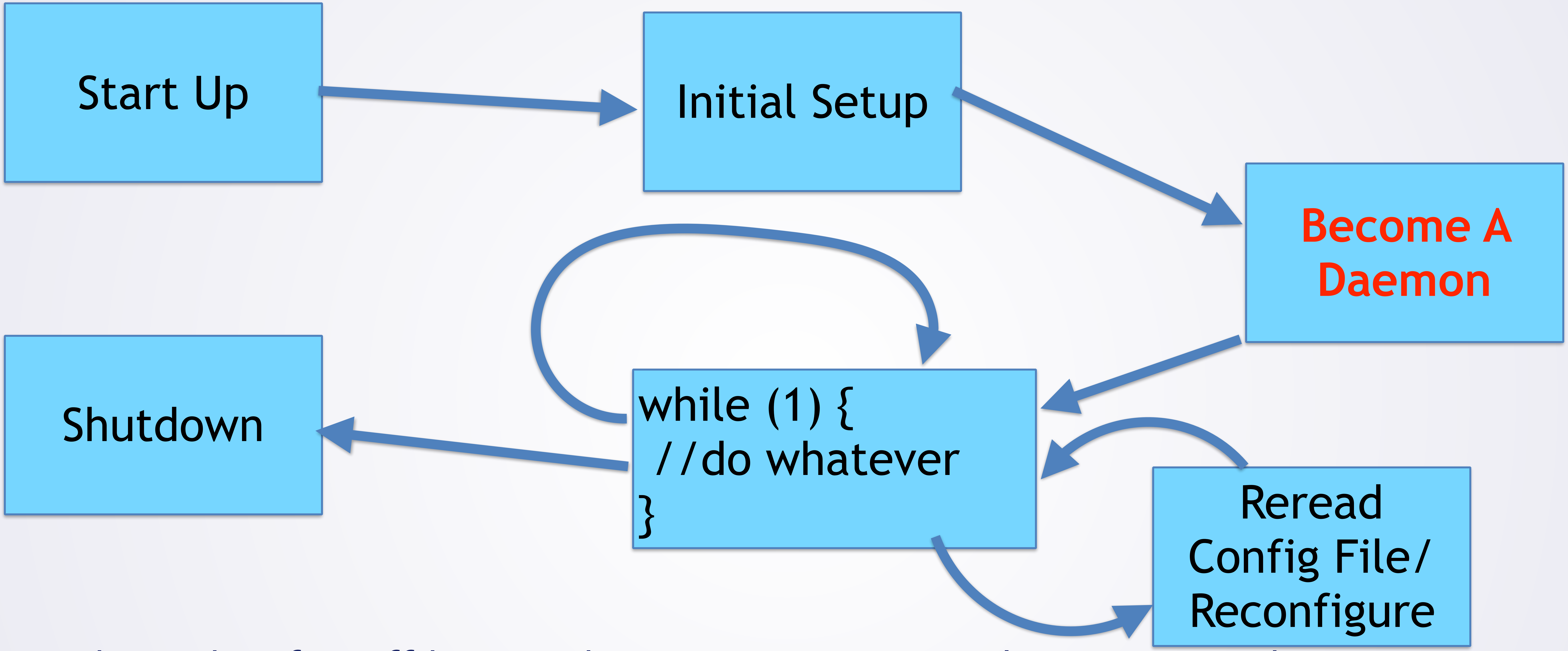
- Old way:
  - Numbered shell scripts, done in order
- Systemd (newer) way:
  - Units with dependencies
  - https://access.redhat.com/documentation/en-US/Red_Hat_Enterprise_Linux/7/html/System_Administrators_Guide/sect-Managing_Services_with_systemd-Unit_Files.html
- Can manually start/restart/status etc with **systemctl**
  - Can also control whether started automatically at boot

Life Cycle



- Daemon may wish to do some setup while "normal" (*) process
  - Read config files, open log files, bind/listen server socket, etc.
  - (*)Some aspects of "normal" may be overridden by system

Life Cycle



- A bunch of stuff has to happen to correctly run as a daemon
  - Requires introducing some new concepts

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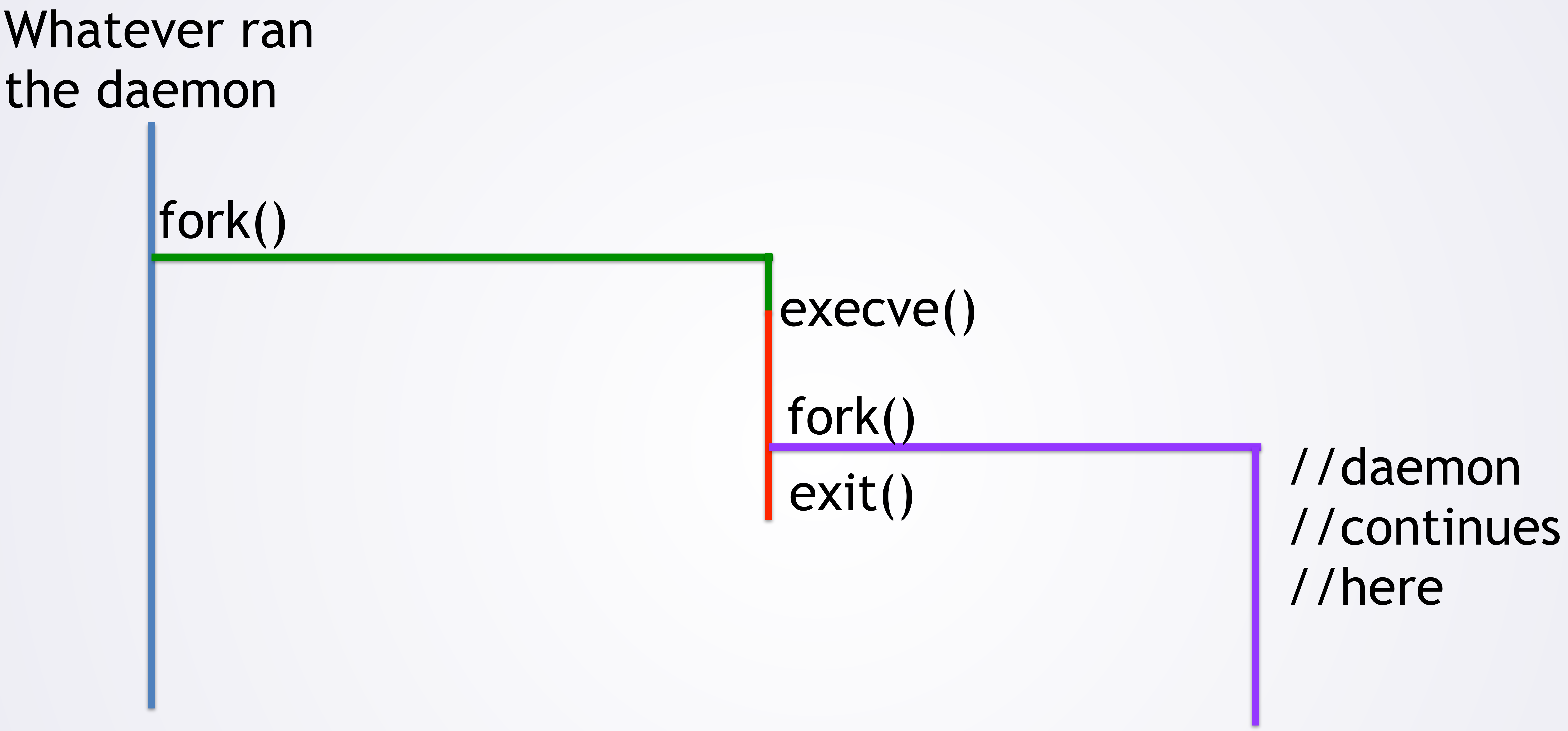
Becoming a Daemon

- Typically Required:
  - fork(), parent exits
  - Dissociate from controlling tty
  - Close stdin/stderr/stdout, open them to /dev/null
  - chdir to "/"

  } **`daemon`** library call

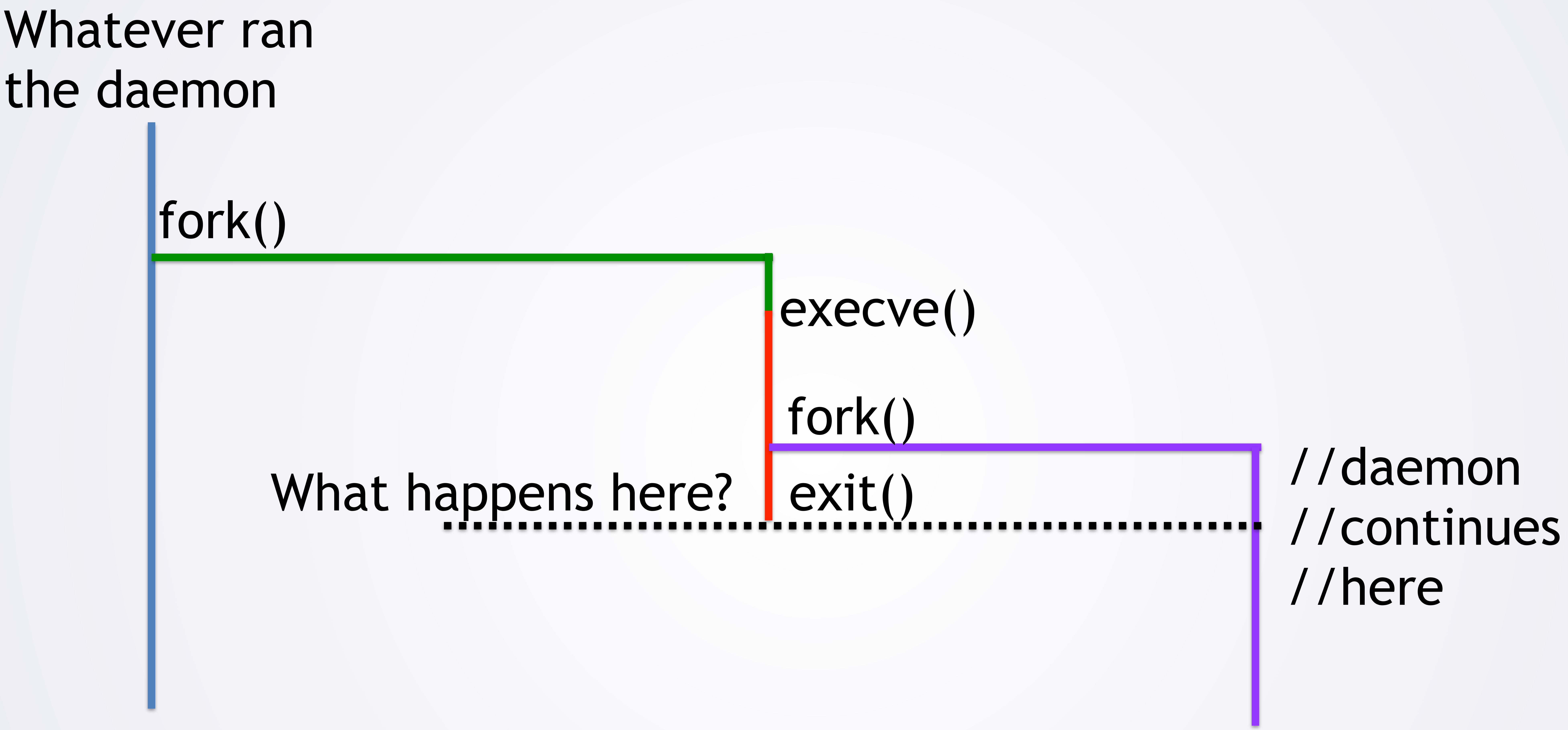
- Good Ideas:
  - Clear umask
  - fork again -> not be session leader

Becoming a Daemon



- fork(), parent exits
  - Why?

Becoming a Daemon



- fork(), parent exits
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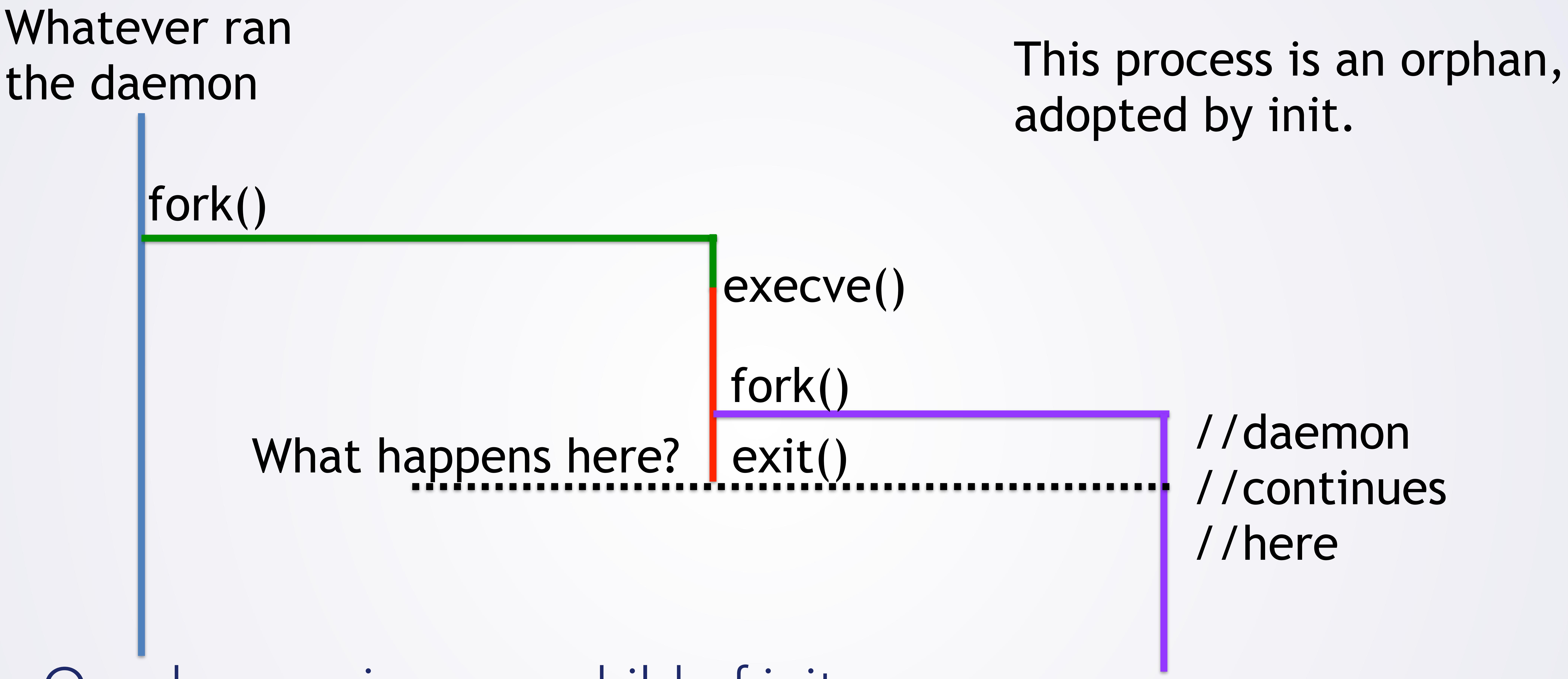
Becoming a Daemon



- Our daemon is now a child of init
- Some shells kill their children when they exit
- Daemon is guaranteed to not be a **process group leader**

Process Groups

```
$
```

shell

- To understand process groups, let us think about some commands..

Process Groups

```
$ find / -name xyz > tmp
```

- To understand process groups, let us think about some commands..

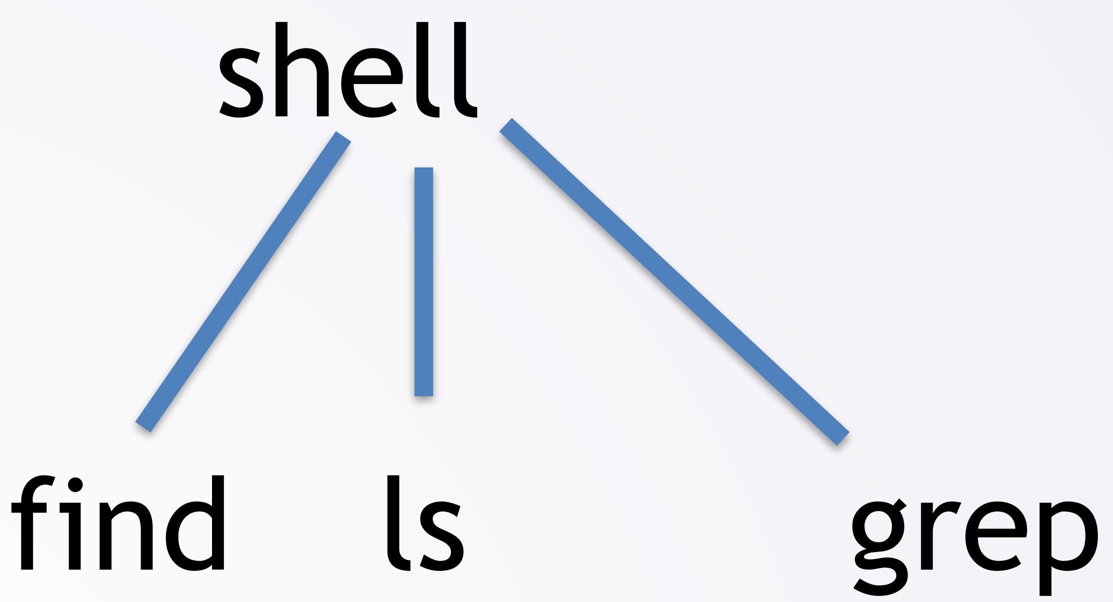
Process Groups

```
$ find / -name xyz > tmp
^Z
$ bg
```

- To understand process groups, let us think about some commands..

Process Groups

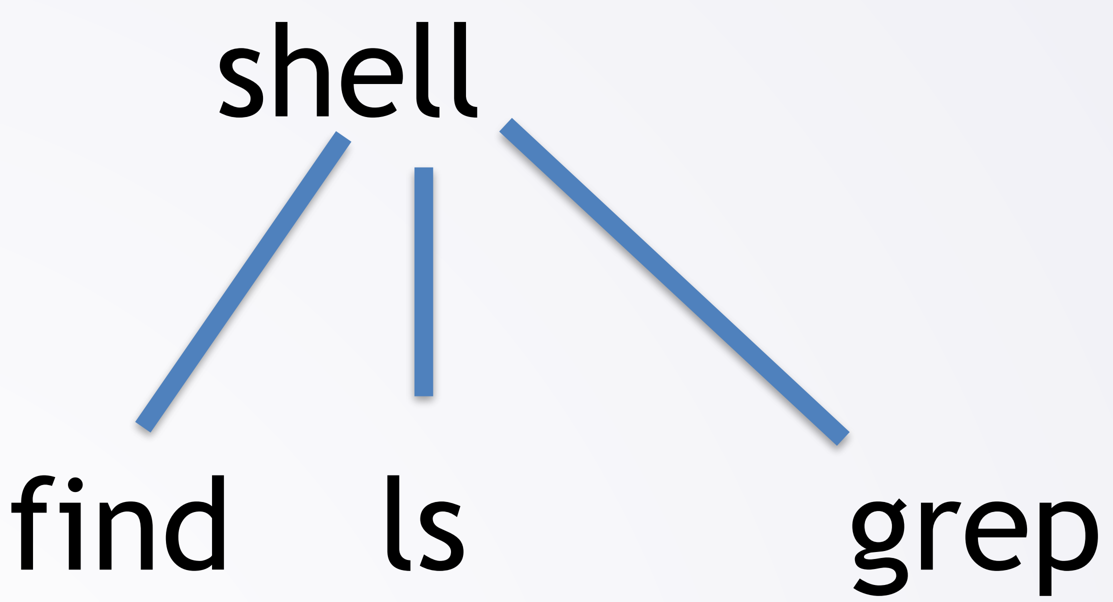
```
$ find / -name xyz > tmp
^Z
$ bg
$ ls *x* | grep y
```



- To understand process groups, let us think about some commands..

Process Groups

```
$ find / -name xyz > tmp
^Z
$ bg
$ ls *x* | grep y
^C
```



- To understand process groups, let us think about some commands..
  - Which process(es) to kill when I type ^C?

Process Groups

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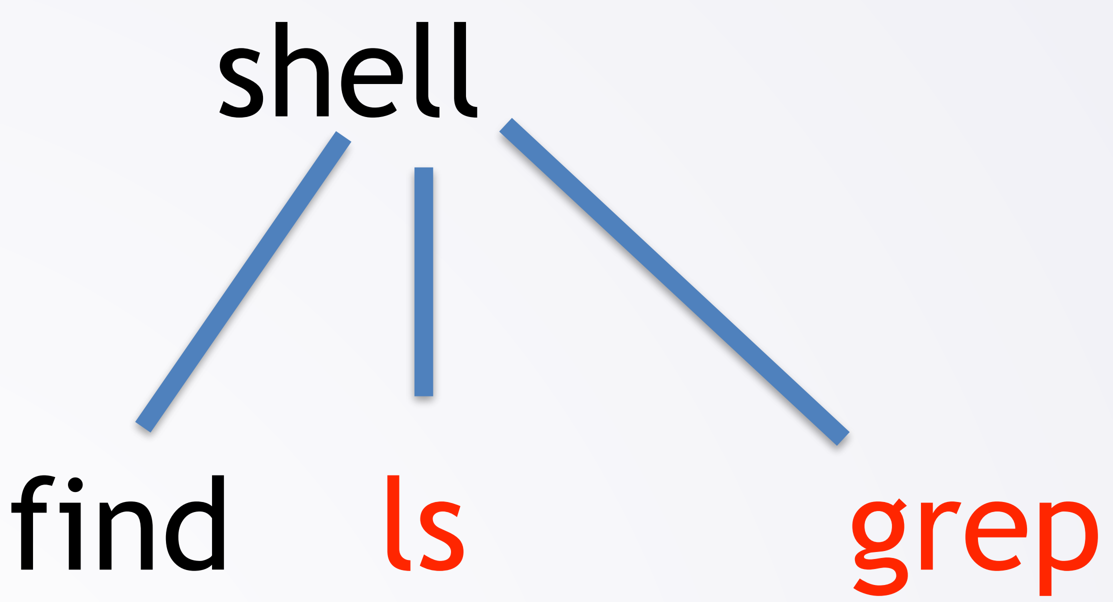
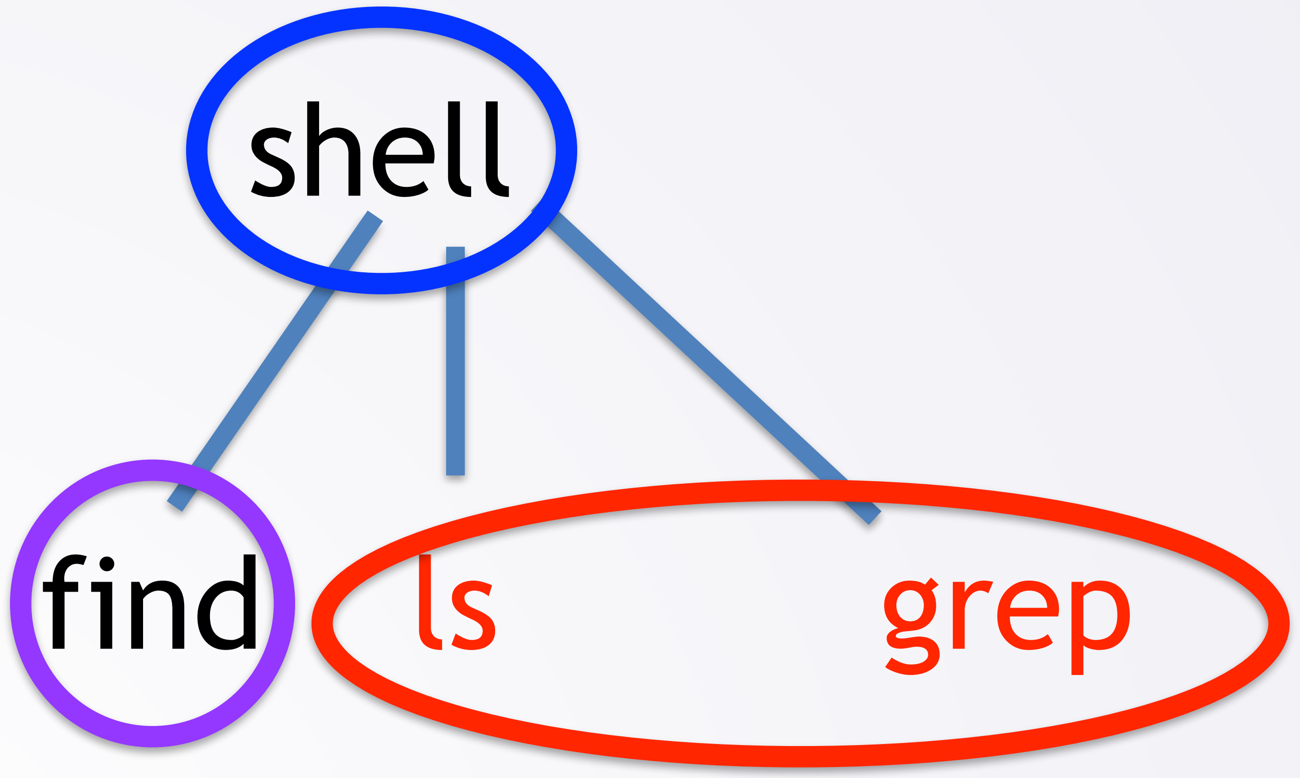


- To understand process groups, let us think about some commands..
  - Which process(es) to kill when I type ^C? **ls + grep**

Process Groups

```
$ find / -name xyz > tmp
^Z
$ bg
$ ls *x* | grep y
^C
```

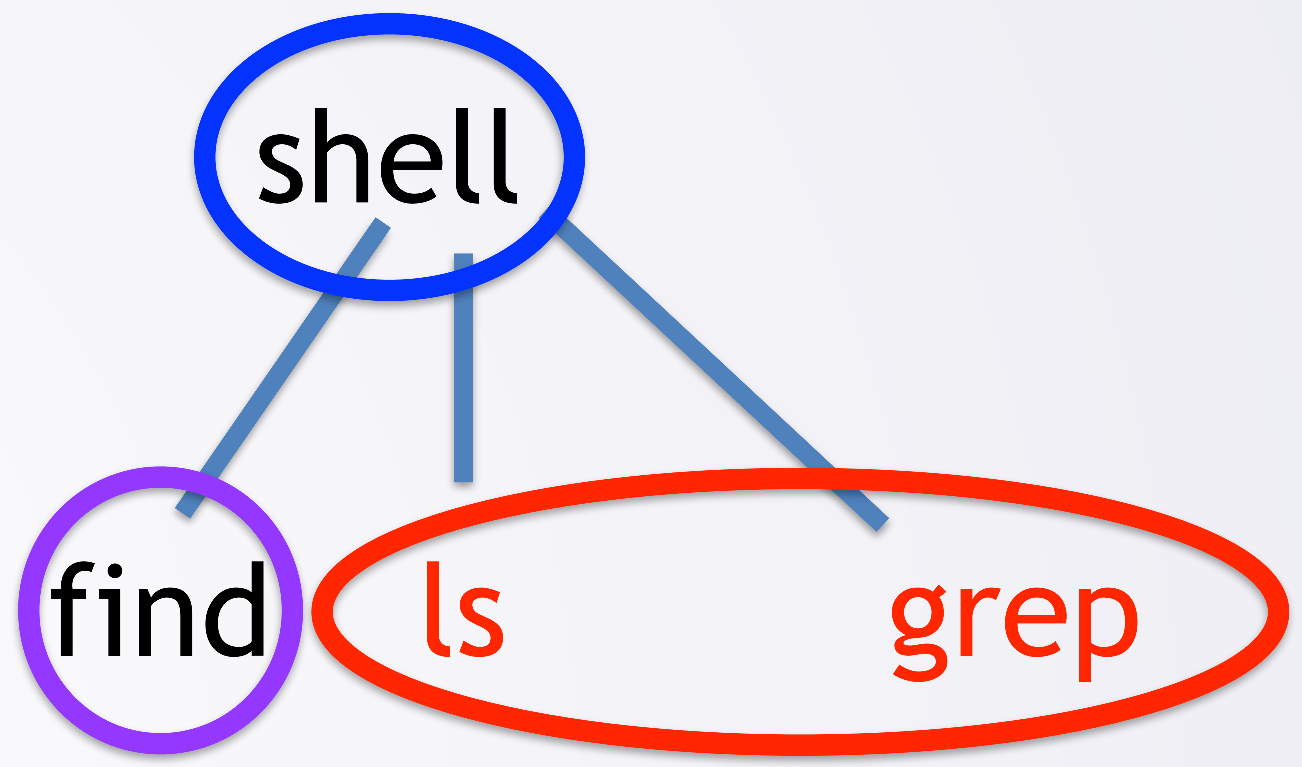


- Related processes organized into "process groups"
  - E.g., one command pipeline = one process group

Process Groups

- Process groups recognized by kernel
  - Various operations are applied to process groups
    - What receive signals from ^C, ^Z, ^\
    - Foreground/background of processes
- Background process groups stop if attempt to read/write terminal
  - Resumed when brought to foreground
- Ok, that's the basics of process groups…
  - …but what do they have to do with becoming a daemon?

Process Groups, Sessions, Controlling TTY



- Process groups relate to **sessions**
  - Sessions relate to **controlling ttys**
  - Daemons cannot have a controlling tty

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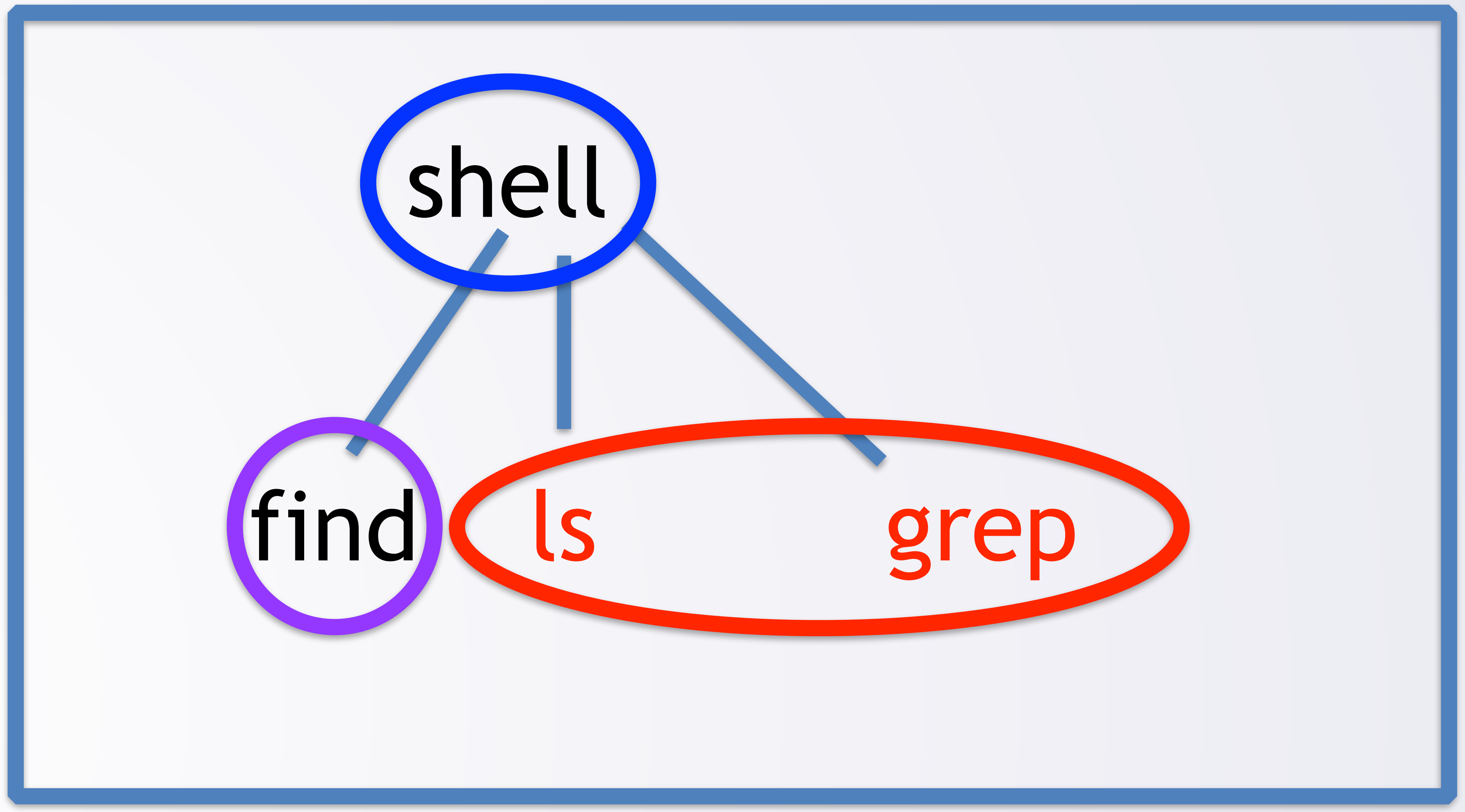
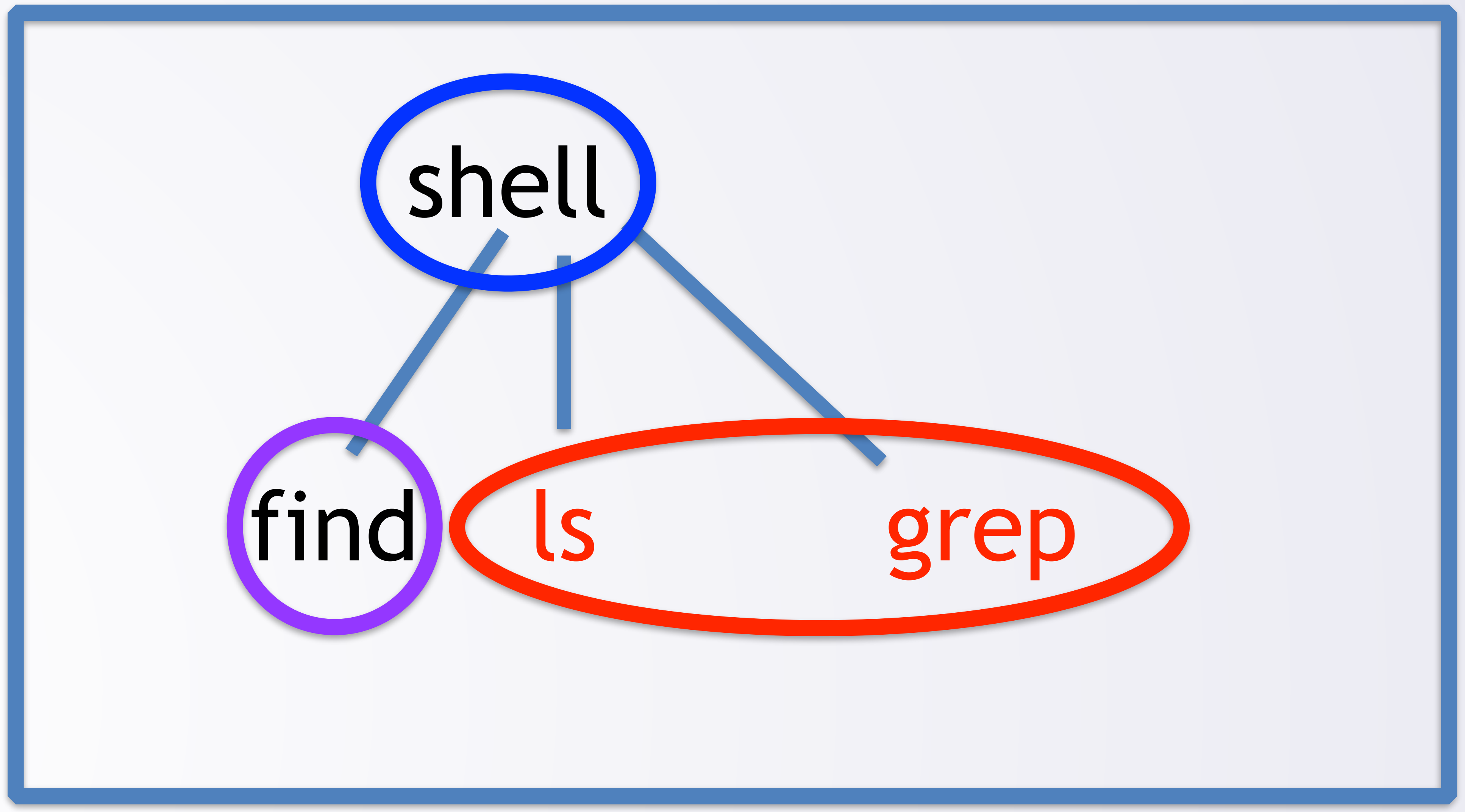
Process Groups, Sessions, Controlling TTY



- The processes are all in one session
  - Session leader is the shell

Process Groups, Sessions, Controlling TTY

```
$ find / -name xyz > tmp
^Z
$ bg
$ ls *x* | grep y
^C
```

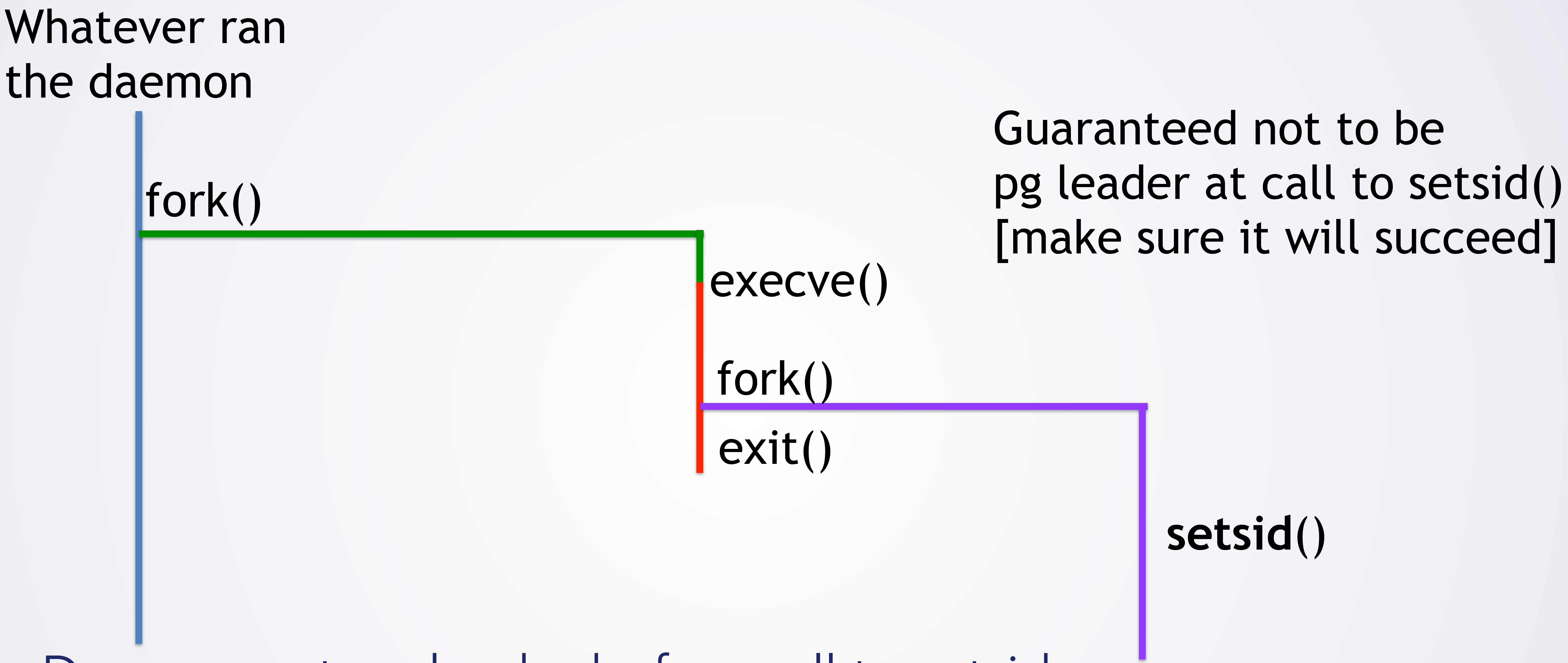


- Session has a controlling tty
  - The terminal that "owns" the processes

New Sessions

- A process can start a new session by calling **setsid**()
  - Process must **NOT** be a process group leader
    - If caller is pg leader, fails.
  - On success:
    - Calling process is process group leader (of a new group)
    - Calling process is session leader (of a new session)
    - Newly created session has no controlling tty

Becoming a Daemon



- Daemon not pg leader before call to setsid

Becoming a Daemon

- Typically Required:
  - **fork(), parent exits**
  - **Dissociate from controlling tty**
  - Close stdin/stderr/stdout, open them to /dev/null
  - chdir to "/"

  } **`daemon`** library call

- Good Ideas:
  - Clear umask
  - fork again -> not be session leader

Point stdin/err/out at /dev/null

- Do not want stdin/err/out associated with old terminal
  - Generally do not want associated with a normal file either
- open /dev/null
  - Use dup2 to close stdin/err/out, and duplicate to fd of /dev/null

Chdir to "/"

- Do not want to keep other directory "busy"
  - If cwd of a process is a directory, it is "in use"
- Change working directory to "/"
  - Will always be in use anyways

Becoming a Daemon

- Typically Required:
  - **fork(), parent exits**
  - **Dissociate from controlling tty**
  - **Close stdin/stderr/stdout, open them to /dev/null**
  - **chdir to "/"**

`daemon` library call

- Good Ideas:
  - Clear umask
  - fork again -> not be session leader

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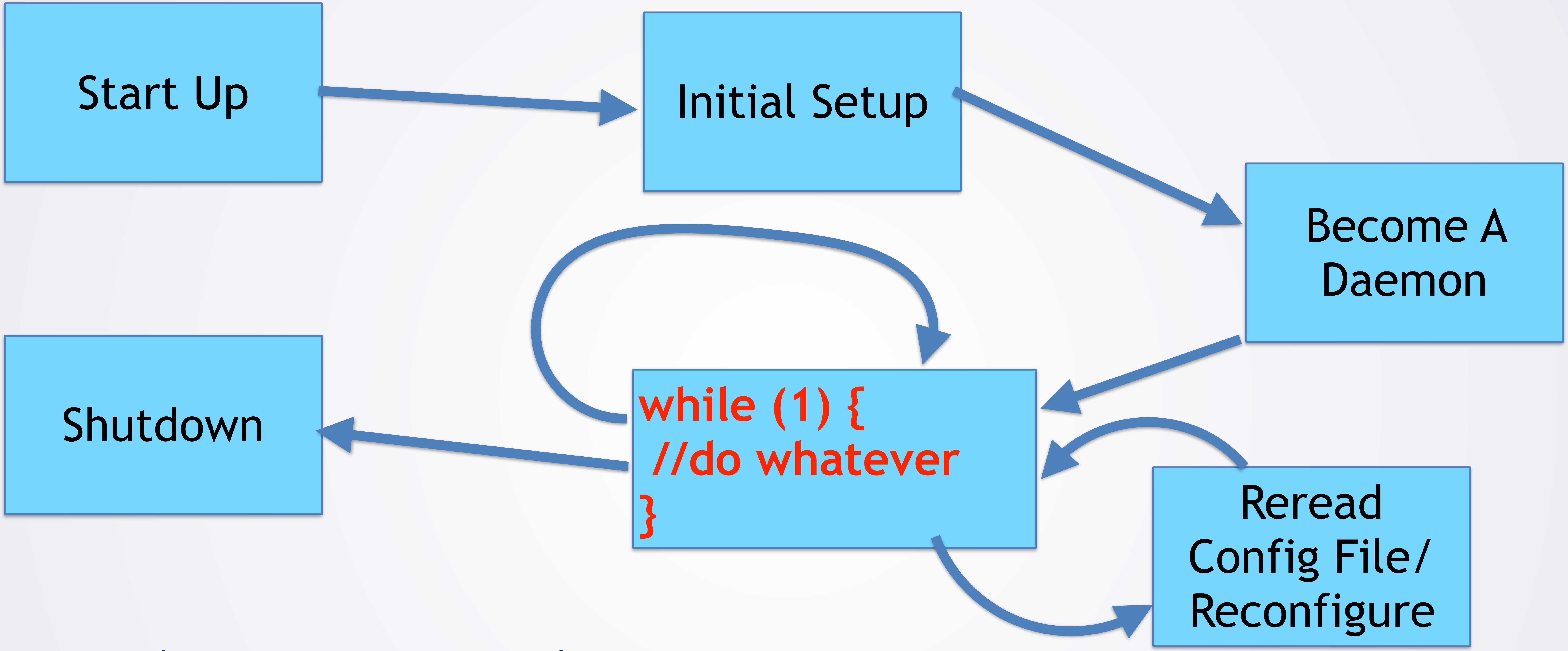
Umask

- Processes have a "umask"—-file creation mask
  - Affects the permissions of files that are created
  - Try to create with `mode`?
    - Actually get `mode & ~umask`
- Why?
  - Security: set default permissions to prevent
- Alter umask with umask system call (see man umask(2)).
  - Specify new mask.
- umask (0) => clear umask (get exactly mod you request)

fork() Again, Do Not Be a Session Leader

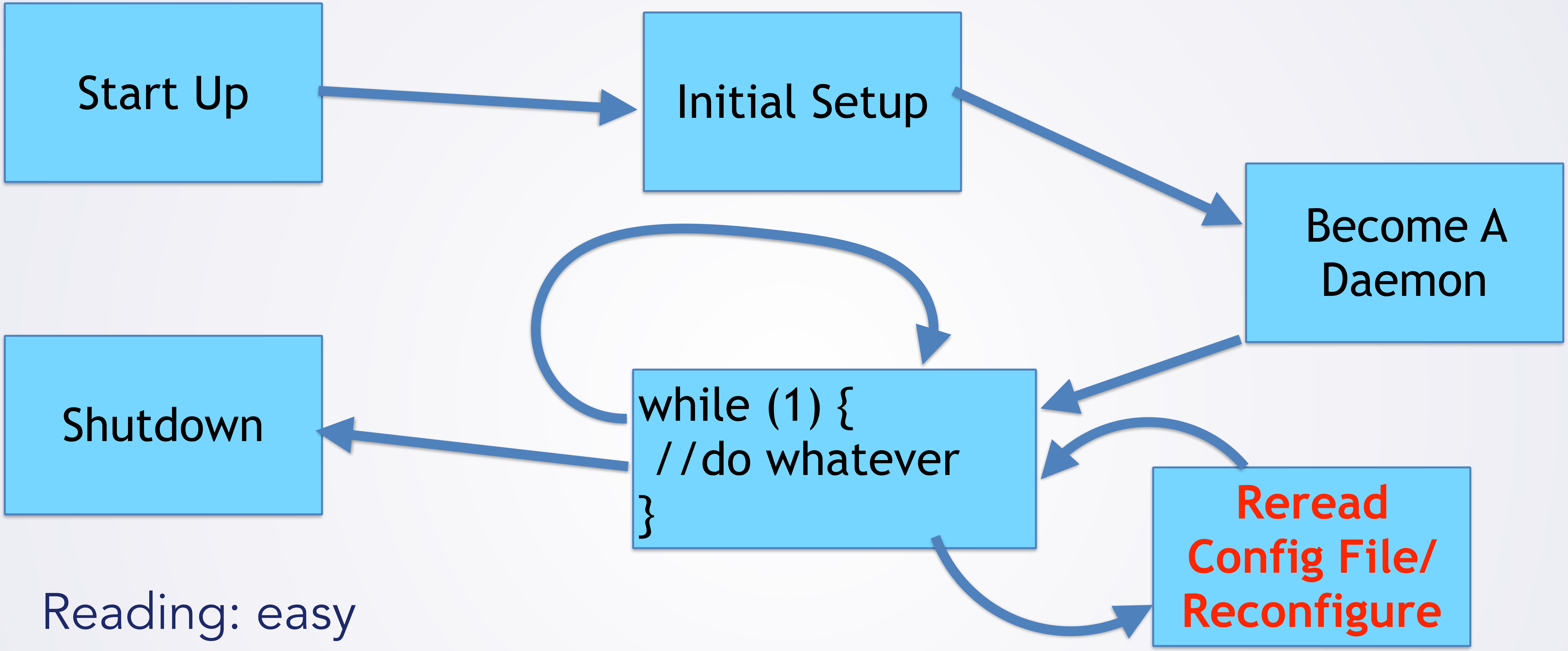
- May be a good idea to fork one more time
  - (How many forks do we need?!?!)
- Another fork() => new process is not session leader
  - Made it session leader to not have controlling tty
  - Now does not have…
- Why?
  - If a session leader without a controlling tty opens a tty…
  - That tty will **become the session's controlling tty :(**
  - Non-session leaders cannot gain a controlling tty

Life Cycle



- Ok, now we are a daemon!
- Time to do useful stuff… forever…?
- Delve into this "stuff" shortly

Life Cycle



- Reading: easy
- Re-configure: maybe tricky (depends on what to do...)
- How do we know **when** to reconfigure?

Common Approach: SIGHUP

- Many daemons interpret the **signal** SIGHUP to mean "reconfigure"
- What are signals?
  - When OS wants to send *asynchronous* notification to process, send signal.
  - Many different signals (each numbered): SIGSEGV, SIGABRT, SIGHUP,…
  - Default actions: terminate (possibly w/ core dump), ignore, stop, continue
    - See man -S7 signal for specifics
  - Signals can also be blocked
- Programs can change behavior with **sigaction**
  - Default, ignore, or programmer-defined function

Using sigaction

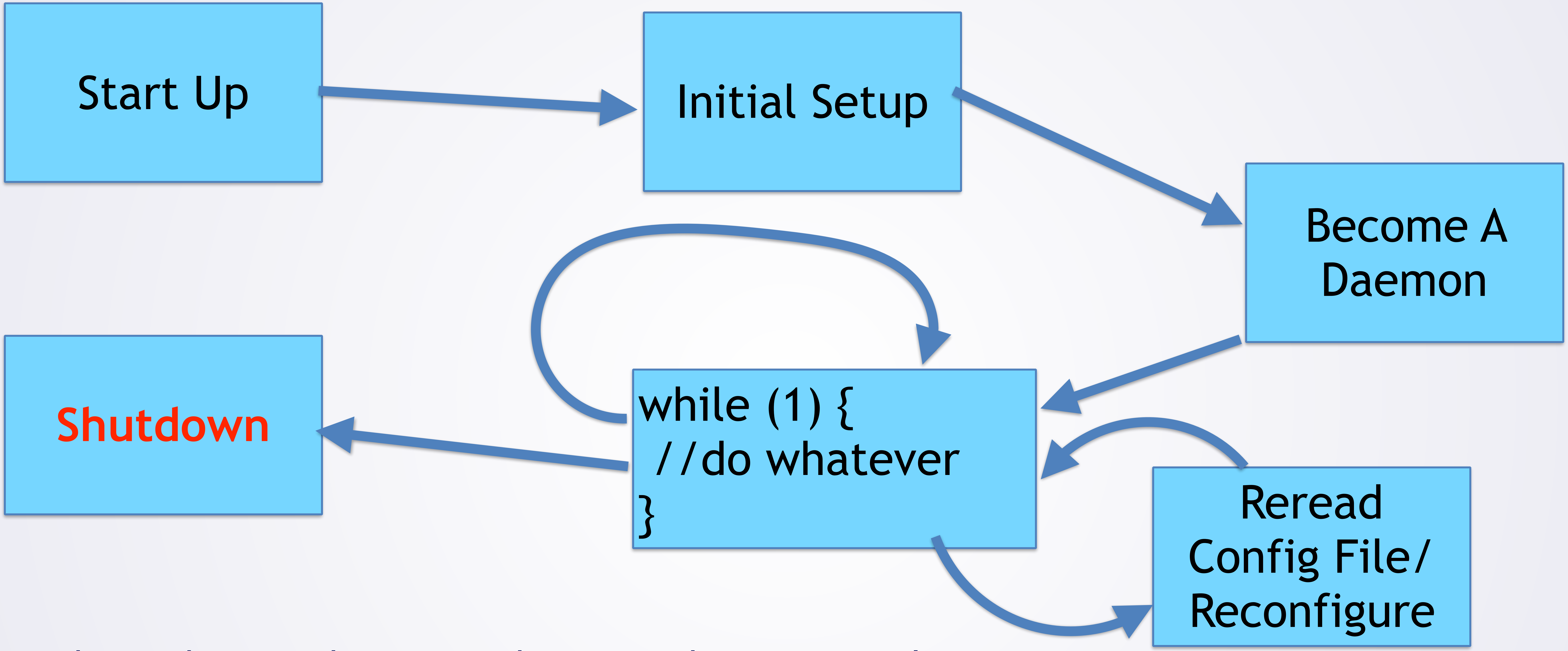
```
struct sigaction sigterm_action;
sigterm_action.sa_handler = my_function;
sigterm_action.sa_flags =  some_flags; //e.g. SA_RESTART
if(sigemptyset(&sigterm_action.sa_mask)!= 0) {
   //handle error
}
//use sigaddset to add other signals to sa_mask
if(sigaction(SIGHUP,&sigterm_action, NULL) != 0) {
    //handle error
}
```

- Basic structure of using sigaction to setup a signal handler

Signal Handler

- Signal handler ("my_function") looks like
  - void my_function (int signal_number) { … }
- You have to be careful what you call/do in it
  - Program may be interrupted in the middle of something
  - Similar problems/ideas to data races with multiple threads
  - Some functions are defined as safe to call in signal handler

Life Cycle



- Shut down daemon by sending signal
  - kill system call sends signal to a process

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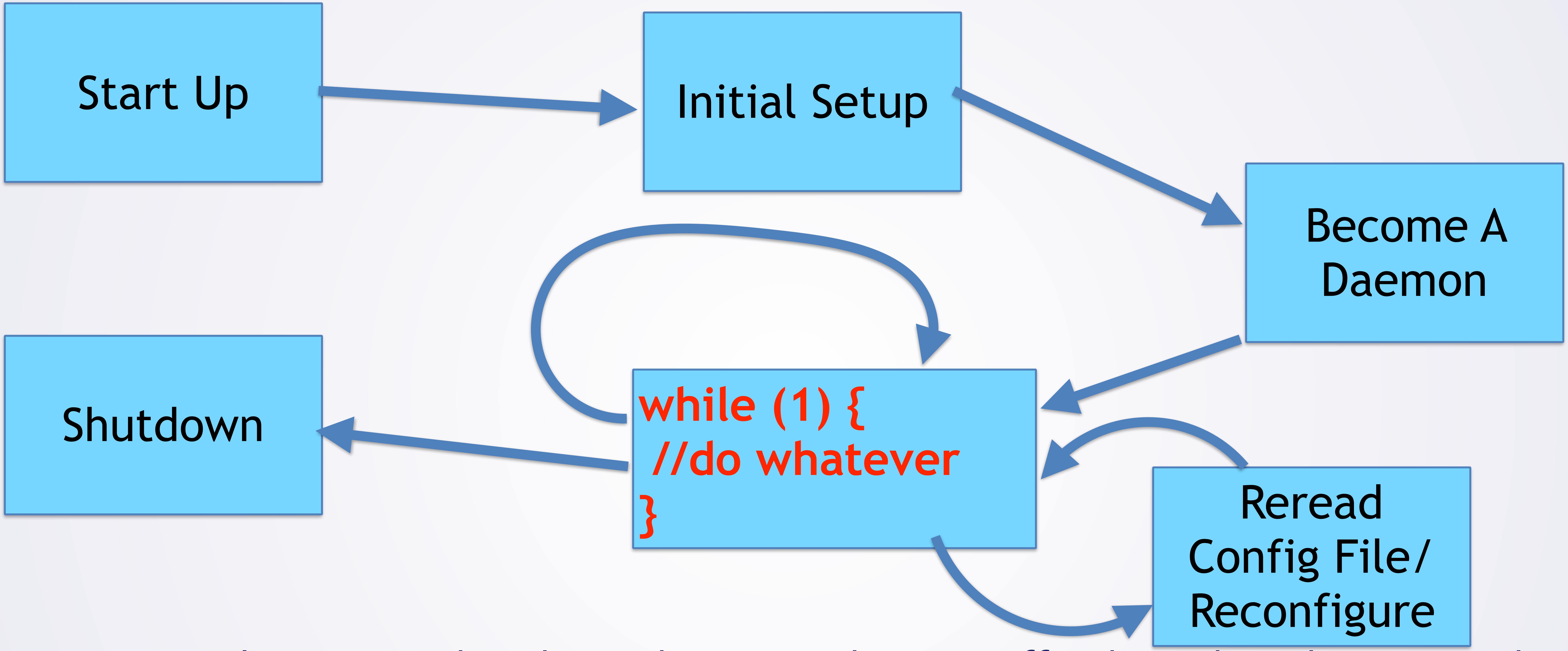
Life Cycle



- Now let us go back and revisit the "stuff" that the daemon does

Accept, Process, Respond [mostly]

```
while (true) {
    req = accept_incoming_request();
    resp = process_request(req);
    send_response(req,resp);
}
```

This might take many forms:
- accept() network socket
- read from FIFO/pipe
- pull from DB table

…

- Not strictly a rule (may communicate both ways, etc)
- But a good "general formula" to start from
- As noted last time: probably want some **parallelism**…

Parallelism

	processes	threads
create per request		
pre-create		

- What does this parallelism look like?
  - 4 main options

fork per-request

```
while (true) {
    req = accept_incoming_request();
    pid_t p = fork();
    if (p < 0) {/*handle error */}
    else if (p == 0) {
      resp = process_request(req);
      send_response(req,resp);
      exit(EXIT_SUCCESS);
    }
    //cleanup: close/free req
    //need to wait for p w/o blocking
}
```

- Pros and cons?

Fork-per-request Pros/Cons

- Pros:
  - Simplicity: avoid difficulties of multi-threaded programming
  - Isolation between requests : separate processes
- Cons:
  - No ability to share state between/across requests
  - fork() latency on critical path
  - Creates arbitrary number of processes

Pre-fork

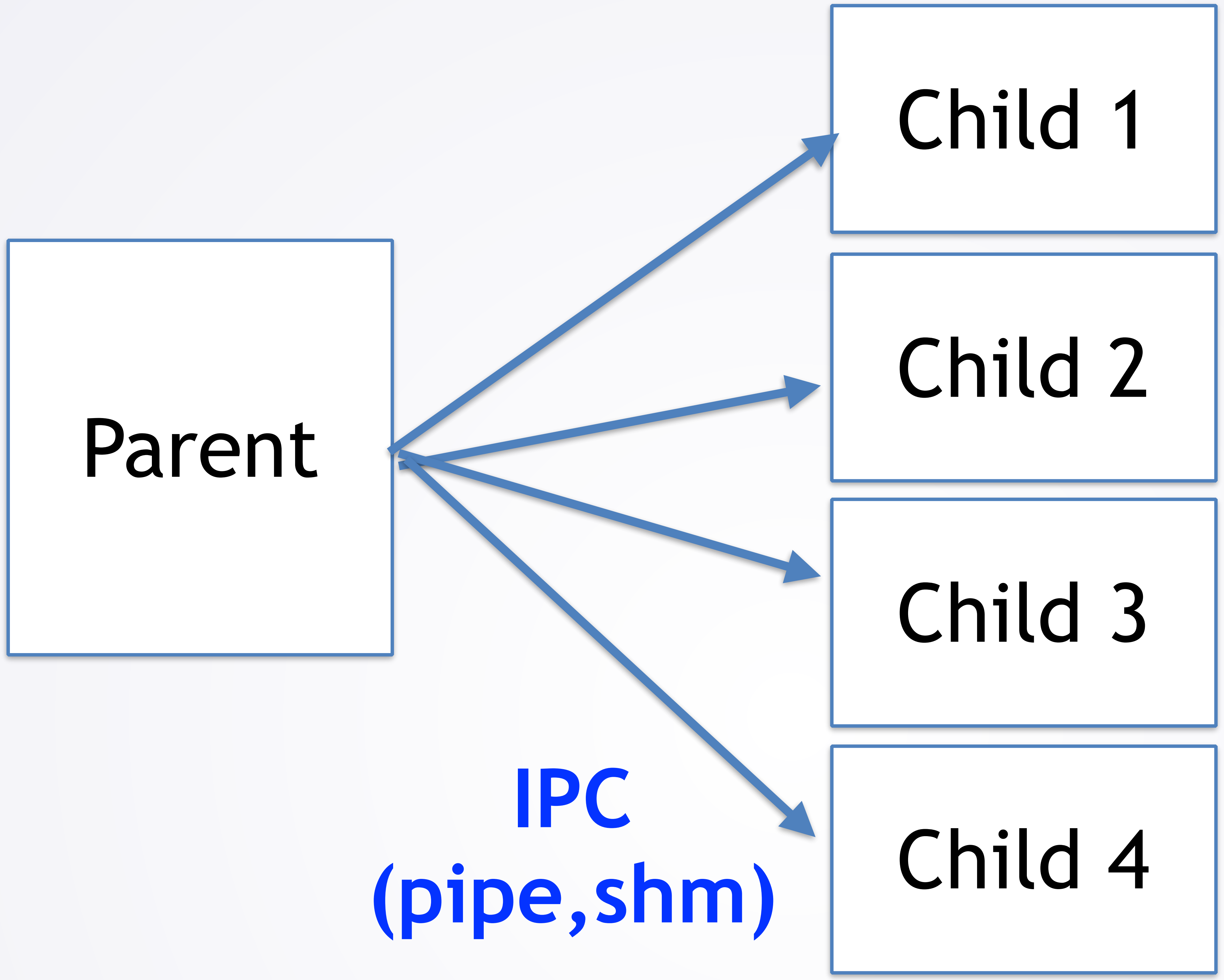
```
for (int i = 0; i < n_procs; i++) {
    pid_t p = fork();
    if (p < 0) { /* handle error */}
    else if (p == 0) {
        request_loop(); //never returns
        abort(); //unreachable
    }
    else {
     children.push_back(p);
    }
}
//What happens here depends…
```

pre-fork request loop

```
void request_loop(void) {
   while (true) {
      req = accept_incoming_request();
      resp = process_request(req);
      send_response(req,resp);
   }
}
```

- How does this work across multiple processes?
  - …it depends…

Parent Dispatches Requests



- One approach: parent dispatches requests:
  - Requests come into parent
  - Parent chooses a child and sends it via IPC (pipe, shared memory,..)

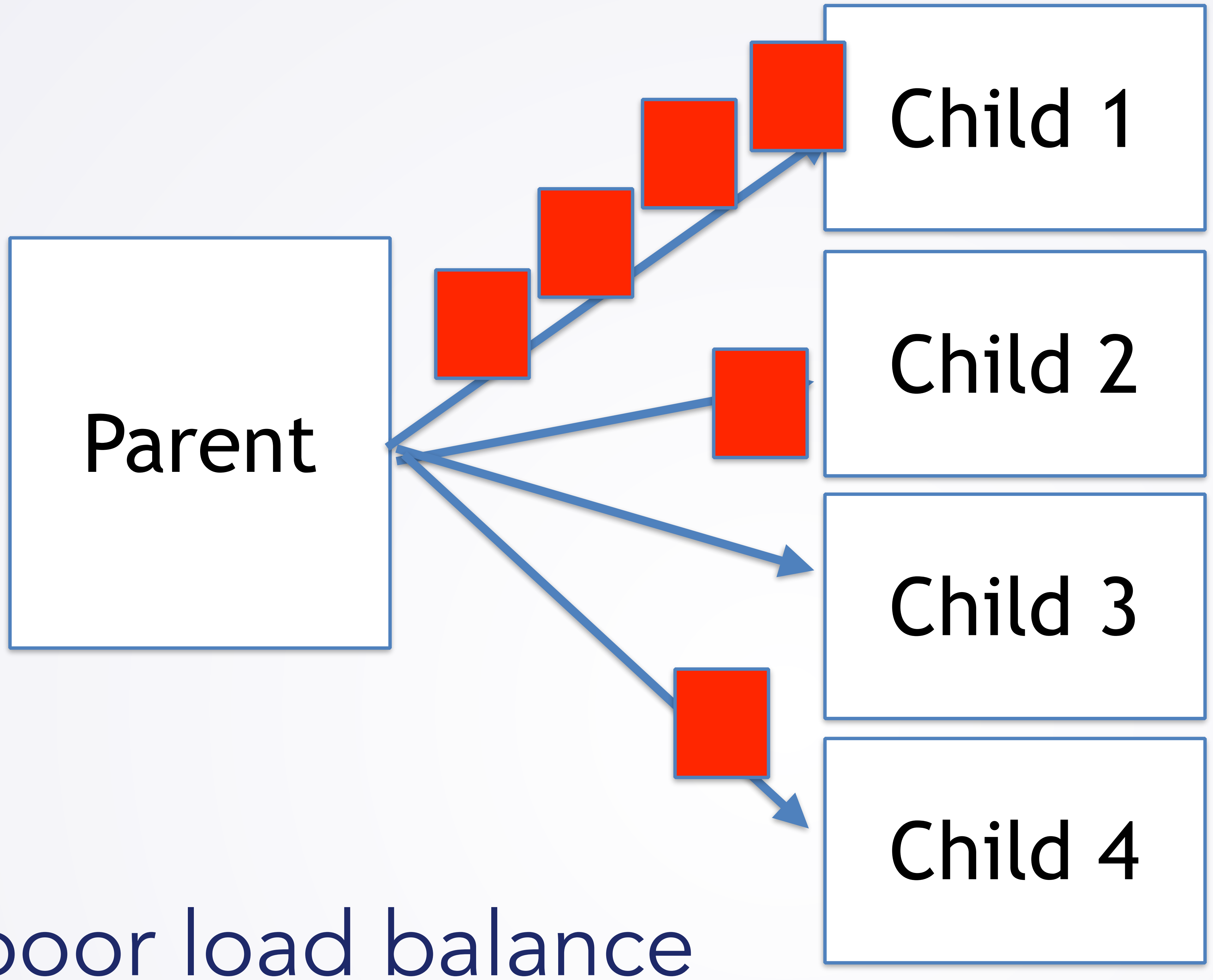
Pre-fork

```
for (int i = 0; i < n_procs; i++) {
    pid_t p = fork();
    if (p < 0) { /* handle error */}
    else if (p == 0) {
        request_loop(); //never returns
        abort(); //unreachable
    }
    else {
     children.push_back(p);
    }
}
request_dispatch_loop(); //accept, send to child
```

Need to add code to setup IPC here (before fork())

Need to record IPC info in data structure

Load Balancing



- System has poor load balance
  - Child 1 is overloaded, Child 3 is underloaded
- What if we dispatch round-robin (1, 2, 3, 4,1, 2, 3, 4),…
  - Requests have different latency -> may still have poor balance

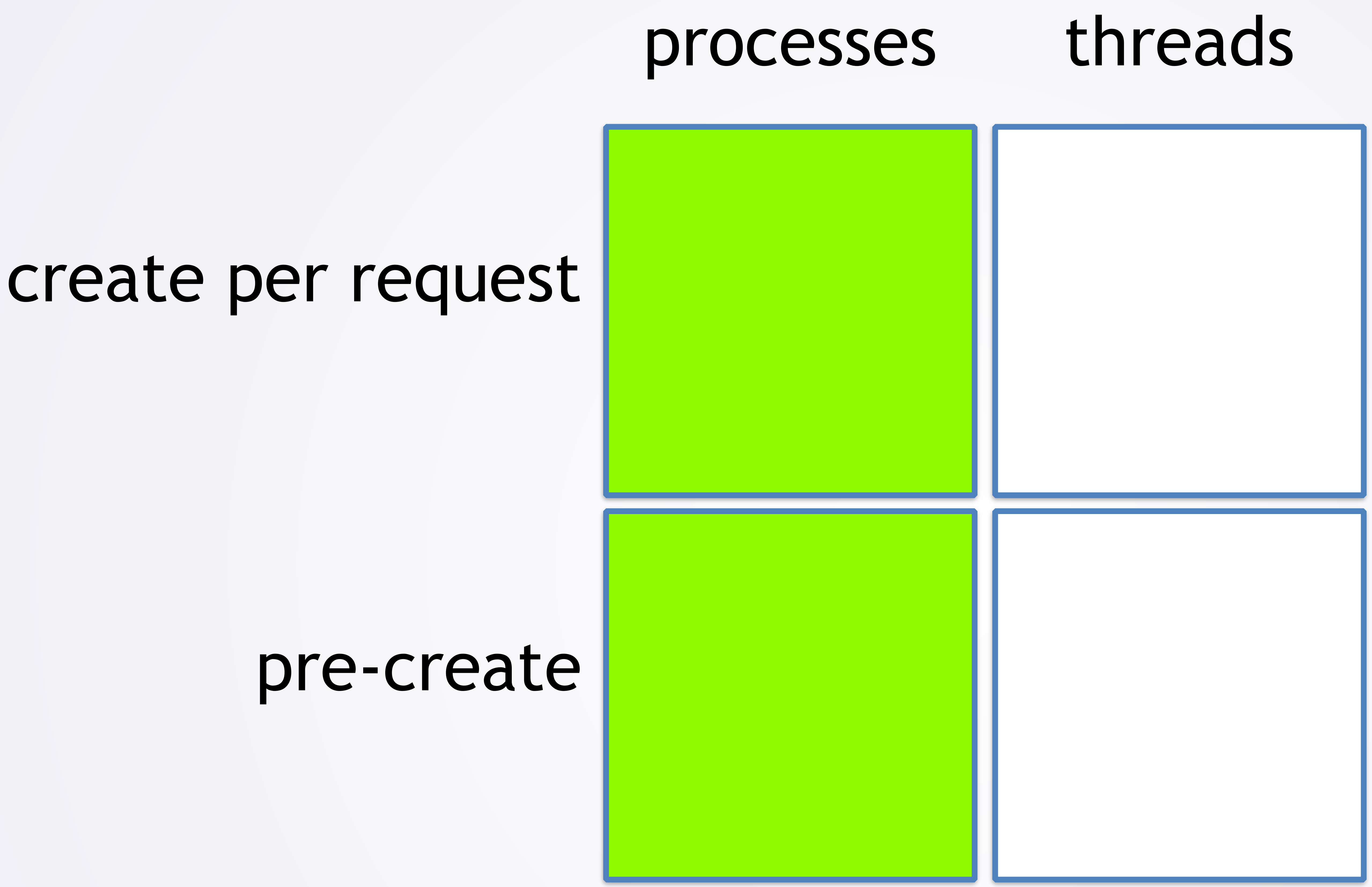
Networking (or other fd-based reqs)

- Previous approach not great for network sockets
  - Can't easily send a socket over a pipe (fd is just a number)
- Common approach: each process calls accept() on same server socket
  - Create socket, bind, listen before fork()
  - Have each process call accept()
  - Safe under Linux, cannot find POSIX guarantees
- Not best for performance
  - Preferable [on Linux]: have each process make own socket
  - Use SO_REUSEPORT socket option: all can bind to same port
    - If interested: https://lwn.net/Articles/542629/

pre-fork

- Pros:
    - Simplicity: avoid difficulties of multi-threaded programming
    - Some isolation between requests
    - Choose number of processes (can even adjust dynamically…)
    - fork() overhead only once at startup
- Cons:
    - No ability to share state between/across requests
    - Not as much isolation as per-request forking
    - [Some forms] More likely to need explicit load balancing

Parallelism



- Talked about process-based approaches (forking)
- Now let's talk about the thread-based ones.

Threads

- Similar code to forking:
  - Replace fork with pthread_create
  - Communication? Simpler: naturally share memory
    - Easier to have shared queue of requests for pre-created threads
- Have to deal with multi-threaded programming
  - Harder parts come exactly when we get benefits from MT over MP
    - Shared state

Thread Per Request

- Pros:
    - Shared State
- Cons:
    - Complexities of multi-threaded programming
    - No isolation
    - No limit on number of threads created (may be highly inefficient)
    - Overhead of pthread_create() is on critical path

Pre-Create Threads

- Pros:
  - Shared State
  - Probably easier load balancing
  - Overhead for pthread_create up front
  - Shared State
  - Easy to control (and adjust) number of threads
- Cons:
  - No isolation
  - Complexities of multi-threaded programming

Which To Pick?

- Which one to pick?
  - Depends on what you need to do
- You should understand the tradeoffs of each option
- Think carefully/critically as you design your server

UNIX: Users, Permissions, Capabilities

- Important considerations for UNIX Daemons
  - What user does it run as?
    - What if it needs *some* **privileged** operations?
  - Relatedly: file permissions/ownership
- Now:
  - Users: uid manipulation, setuid programs
  - File permissions
  - Capabilities

UNIX Users

- You are used to running as a "normal" user
  - But now you have "root" on a machine..
- root is the privileged user: uid 0
  - Aka "super user"
- Can perform operations that normal users cannot
  - Load kernel modules
  - Adjust system settings
  - Listen on privileged ports (< 1024)
  - Change to other users…
  - …

ROOT IS DANGEROUS

- Anything running as root is **DANGEROUS**
  - Can do anything to the system
    - Add accounts, change password
    - Setup key loggers
    - Hide its own existence
  - 650 later this semester: will make rootkit
- Want to minimize what happens as root
  - When possible, run as "nobody"

setuid(): switch users

- Do privileged operations, then switch users
  - setuid(…);
- Example:
  - Start as root
  - bind to/listen on privileged port
  - setuid(…)
- Useful if all privileged operations are needed up front

Real, Effective, Saved UID

- There are three UIDs for each process:
  - Real user id: the user id of the user who ran it
  - Effective user id: the user id currently used for permission checking
  - Saved set-user-id: remembers "set-user-id" on suid binaries
- Set-user-id binaries:
  - File permissions that specify to switch euid at the start of execution
  - This is what lets programs like sudo, su, etc work

UID Example

```
int main(void) {
  uid_t temp = getuid();
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  seteuid(temp);
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  seteuid(0);     fails (EPERM)
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  return EXIT_SUCCESS;
}
```

uid: 1001
euid: 1001
uid: 1001
euid: 1001
uid: 1001
euid: 1001

- Compile, run as user 1001

UID Example

```
int main(void) {
  uid_t temp = getuid();
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  seteuid(temp);
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  seteuid(0);  Succeeds: Saved-set-user-id is 0
  printf("uid: %d\n", getuid());
  printf("euid: %d\n", geteuid());
  return EXIT_SUCCESS;
}
```

```
uid: 1001
euid: 0
uid: 1001
euid: 1001
uid: 1001
euid: 0
```

- sudo chown root.root a.out
- sudo chmod u+s a.out   //make program suid: USE WITH CAUTION!

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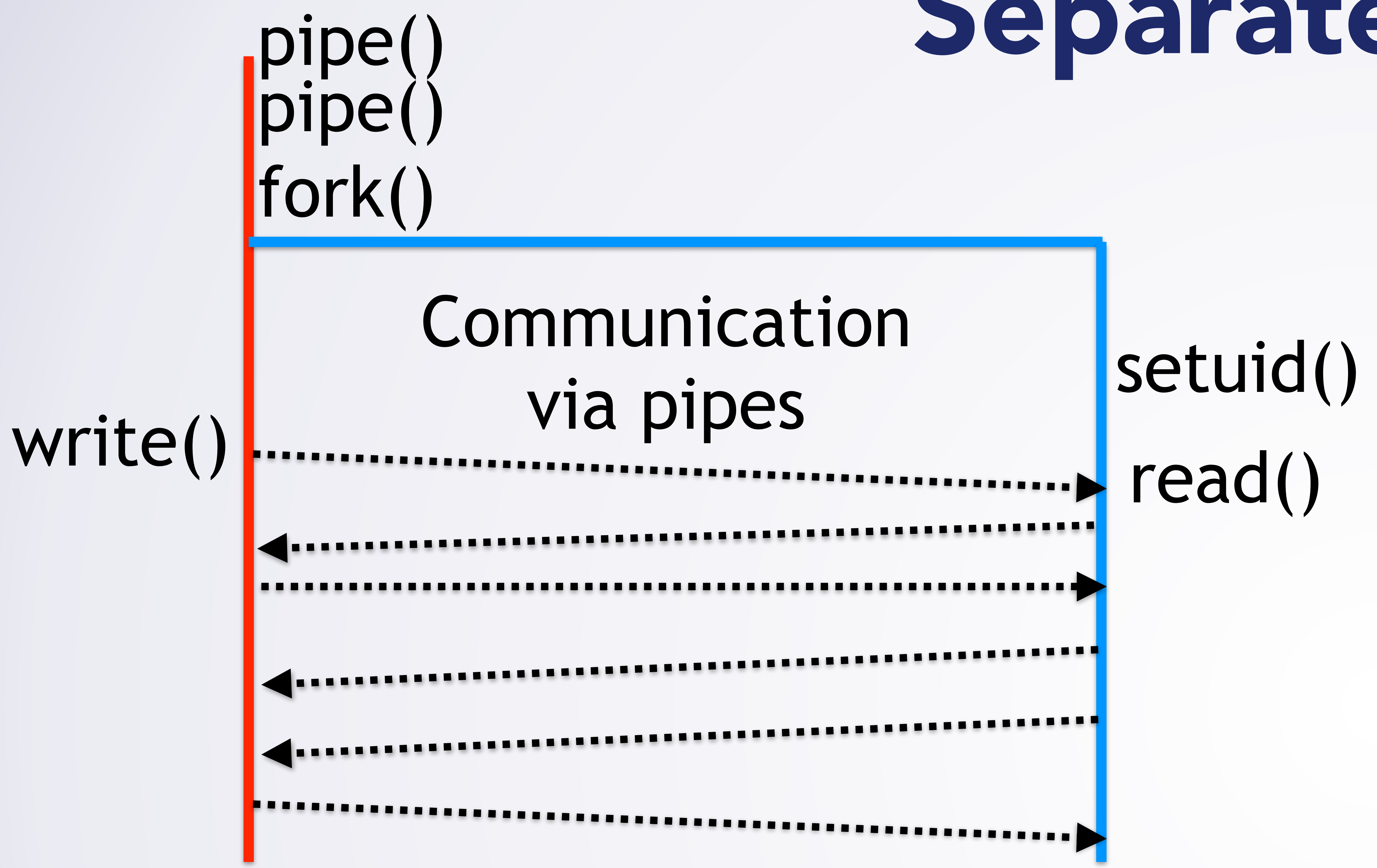
UID Example

```
int main(void) {
  uid_t temp = getuid();
  //Dangerous: root permissions
  seteuid(temp);
  //Safer: user 1001 permissions
  seteuid(0);
  //Dangerous again
  return EXIT_SUCCESS;
}
```

- This program is safer when euid is not 0
- Not completely safe: arbitrary code exploit can seteuid(0)

Separate Processes



- Privileged process can fork
  - New process can completely drop privileges (call setuid() to change all uids)
- Communication can be done with your favorite IPC

Linux Capabilities

- Linux (since 2.2) has the concept of **capabilities**
  - Divides root's super-user powers into sub-abilities (~40)
  - Example: CAP_NET_BIND_SERVICE — bind to port < 1024
- Why useful?
  - If all you need is to bind a privilege port, can have
  - Without ability to do other things (load modules, change permissions,…)
- Executables can be granted individual capabilities
  - Rather than full set-uid status

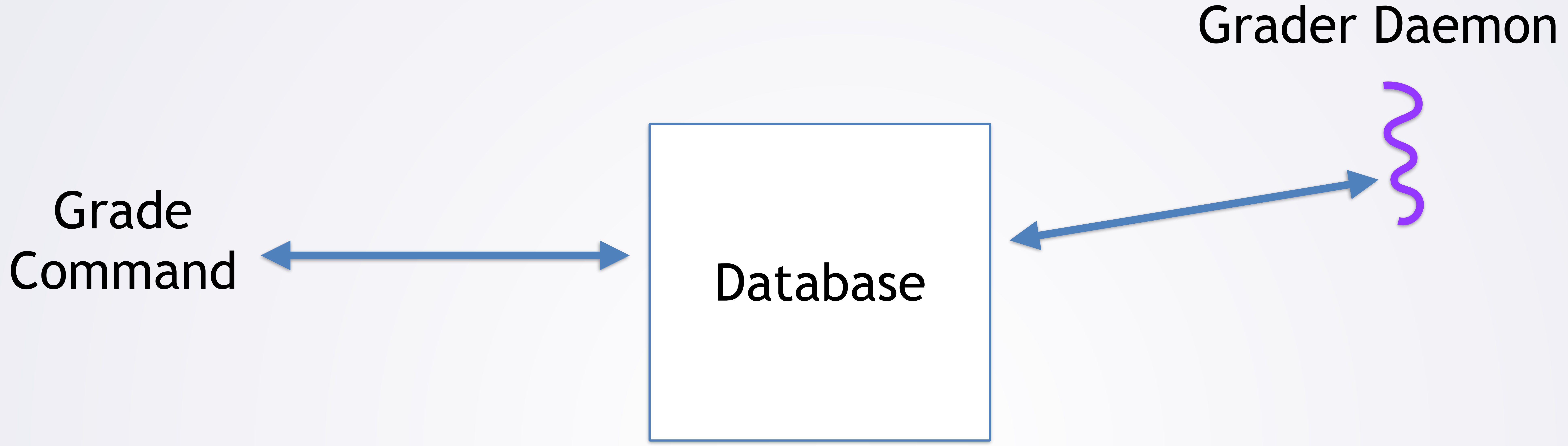
Other User/Permissions Things

- Similar concepts/system calls apply/exist for group ids
  - Programs can be "set group id"
- There is also a "file system user id"—not so common to use

Case Study: ECE 551 Grader System

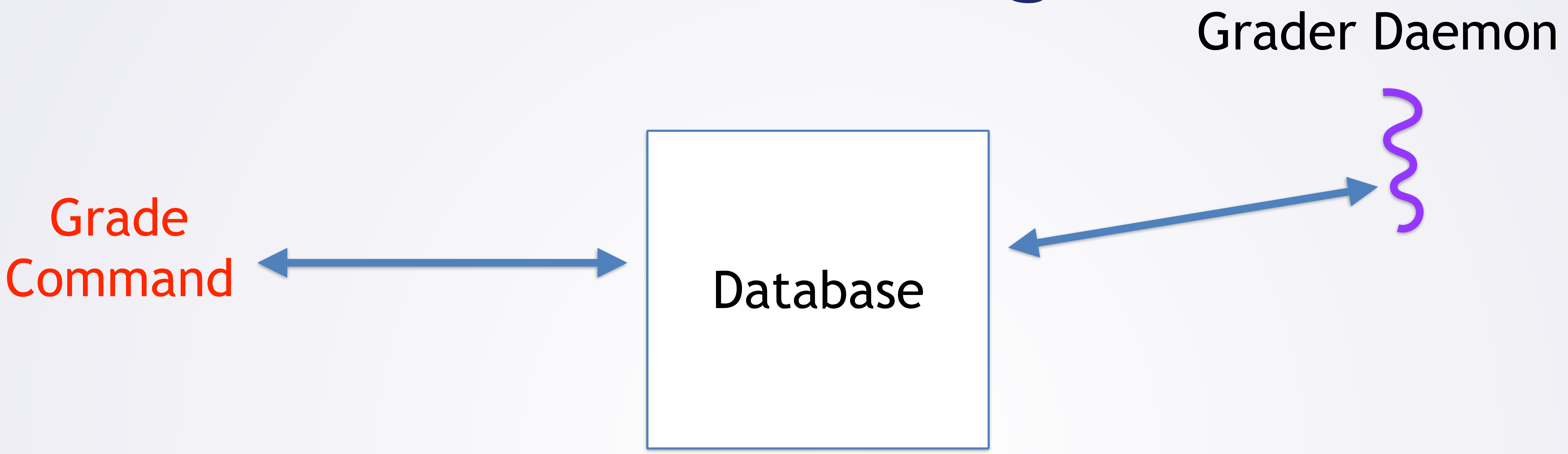
- Everyone's favorite piece of server software!
  - Very interesting from a system design perspective
- Requirements:
  - Run arbitrary (student) code w/o security risk
    - Not concerned about things you could do at shell
    - Concerned about access to grades/grader
  - Simple/low overhead commands [do not require password each time]
  - Interface with git

Grading



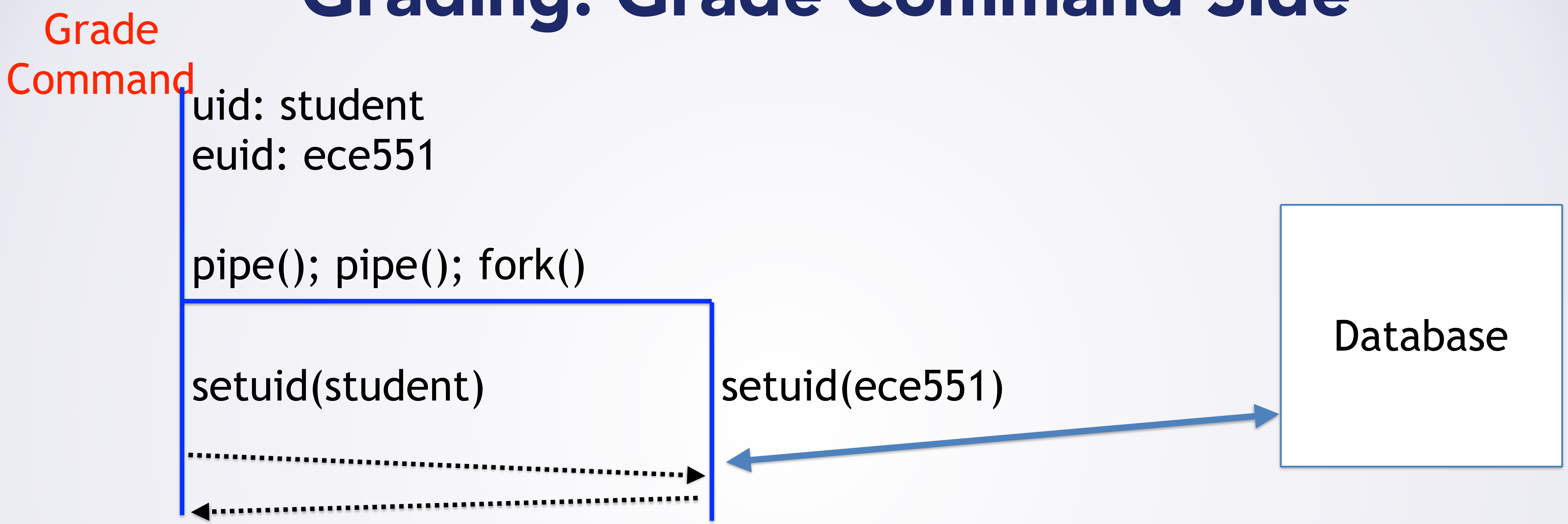
- Student runs grade command
- Grader daemon responsible for grading
- Database holds state

Grading



- Grade command: runs as student
  - But accesses database
- How do we prevent student from accessing db directly?

Grading: Grade Command Side



- grade is setuid ece551
  - Sets up pair of pipes, then fork()s
  - One process becomes "student side", other "ece551 side"
  - Communication over pipes with Google Protocol Buffers

Grading: Daemon Side

Grader Daemon

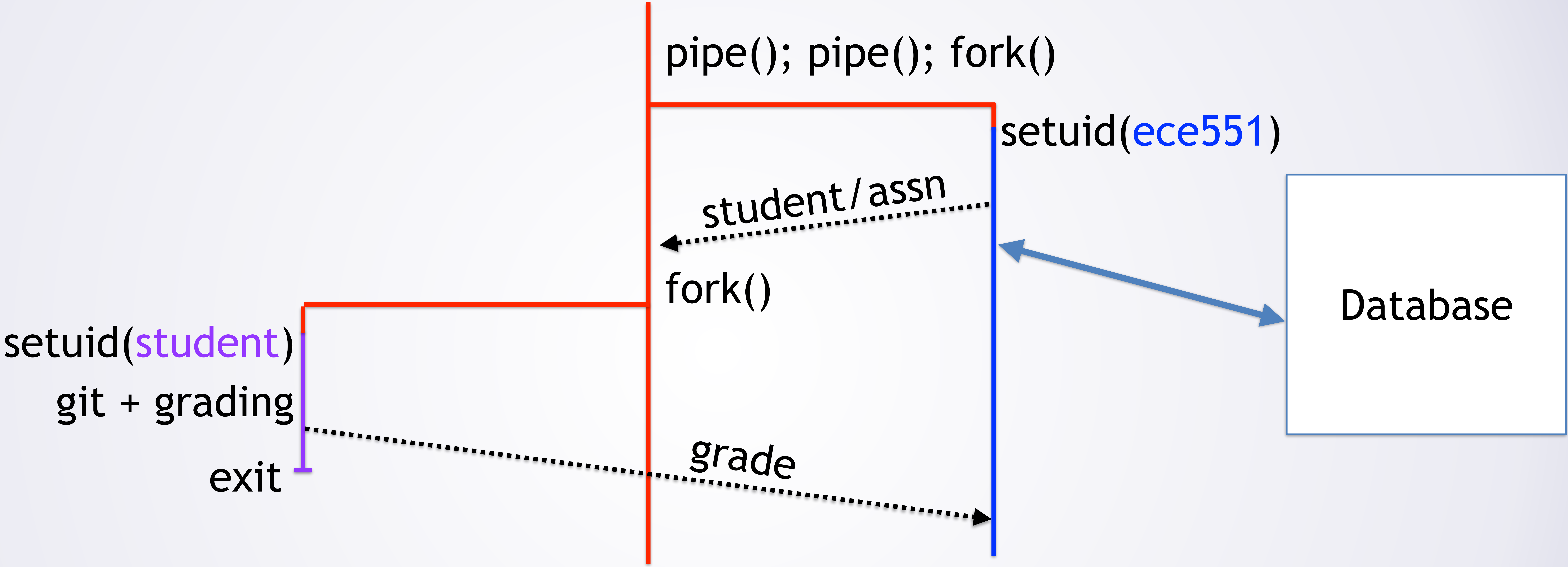

```
while (true) {
    req = accept_incoming_request();
    resp = process_request(req);
    send_response(req,resp);
}
```

- Same structure we've seen before
  - Accept request: from database **Run as ece551**
  - Process: grade it **Run as...?**
  - Send request: update DB **Run as ece551**

Doing Actual Grading

- Need to access student repository: push + pull
  - Want student repo permissions restricted to only student
  - …so run as student?
- Want actual student code to be run as **nobody**
  - Minimal permissions
  - …but also need code to not be able to read grader files [answers,etc]
- So to process a request:
  - git pull [as student]
  - run code/grader [as nobody—-without grader readable by nobody?]
  - git push [as student]

Graderd



- graderd is suid **root**!
  - How does the grading get done as nobody? Another program