ADRIAN PERRIG & TORSTEN HOEFLER

Networks and Operating Systems (252-0062-00)
Chapter 4: Synchronization

Source: xkcd

Example: Linux o(1) scheduler

- **140 level Multilevel Feedback Queue**
  - 0-99 (high priority):
    static, fixed, “realtime”
    FCFS or RR
  - 100-139: User tasks, dynamic
    Round-robin within a priority level
    Priority ageing for interactive (I/O intensive) tasks

- **Complexity of scheduling is independent of no. tasks**
  - Two arrays of queues: “runnable” & “waiting”
  - When no more task in “runnable” array, swap arrays

Example: Linux "completely fair scheduler"

- **Task's priority = how little progress it has made**
  - Adjusted by fudge factors over time
  - Get "bonus" if a task yields early (his time is distributed evenly)

- **Implementation uses Red-Black tree**
  - Sorted list of tasks
  - Operations now O(log n), but this is fast

- **Essentially, this is the old idea of "fair queuing" from packet networks**
  - Also called "generalized processor scheduling"
  - Ensures guaranteed service rate for all processes
  - CFS does not, however, expose (or maintain) the guarantees

Problems with UNIX Scheduling

- **UNIX conflates protection domain and resource principal**
  - Priorities and scheduling decisions are per-process (thread)

- **However, may want to allocate resources across processes, or separate resource allocation within a process**
  - E.g., web server structure

    Multi-process

    Multi-threaded

    Event-driven
  - If I run more compiler jobs than you, I get more CPU time

- **In-kernel processing is accounted to nobody**

Resource Containers [Banga et al., 1999]

New OS abstraction for explicit resource management, separate from process structure

- **Operations to create/destroy, manage hierarchy, and associate threads or sockets with containers**
- **Independent of scheduling algorithms used**
- **All kernel operations and resource usage accounted to a resource container**

⇒ **Explicit and fine-grained control over resource usage**

⇒ **Protects against some forms of DoS attack**

- **Most obvious modern form: *virtual machines, containers***

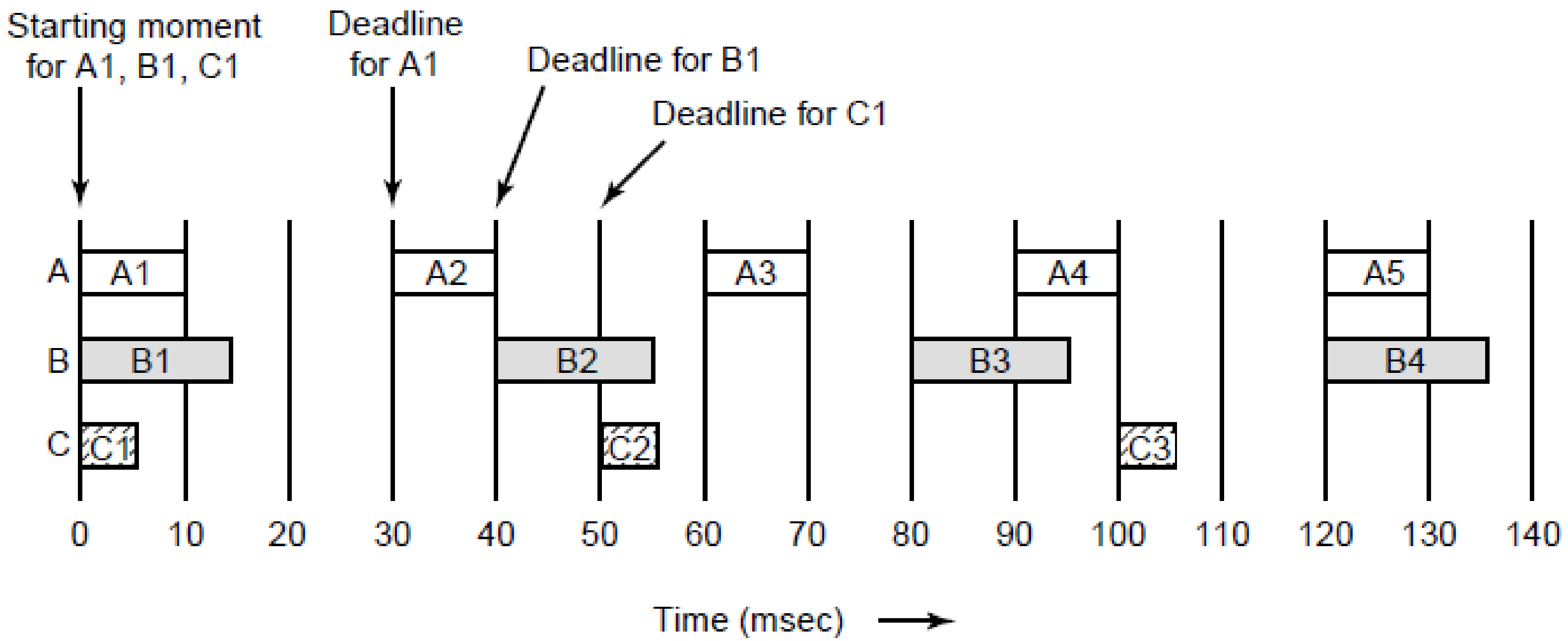
Real Time

Real-time scheduling

- **Problem: giving real time-based guarantees to tasks**
  - Tasks can appear at any time
  - Tasks can have deadlines
  - Execution time is generally known
  - Tasks can be periodic or aperiodic

- **Must be possible to reject tasks which are unschedulable, or which would result in no feasible schedule**

Example: multimedia scheduling



Rate-monotonic scheduling

- **Schedule periodic tasks by always running task with shortest period first.**
  - Static (offline) scheduling algorithm

- **Suppose:**
  - m tasks
  - C_i is the execution time of i'th task
  - P_i is the period of i'th task

- **Then RMS will find a feasible schedule if:**

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq m\left(2^{1/m} - 1\right)$$

- **(Proof is beyond scope of this course)**

cf. Liu, Leiland: "Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment", JACM 1973

Earliest deadline first

- **Schedule task with earliest deadline first (duh..)**
  - Dynamic, online.
  - Tasks don’t *actually* have to be periodic…
  - More complex – at first sight O(n) for scheduling decisions

- **EDF will find a feasible schedule if:**

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

- **Which is very handy. Assuming zero context switch time…**

Guaranteeing processor rate

- **E.g., you can use EDF to guarantee a rate of progress for a long-running task**
  - Break task into periodic jobs, period *p* and time *s*.
  - A task arrives at start of a period
  - Deadline is the end of the period

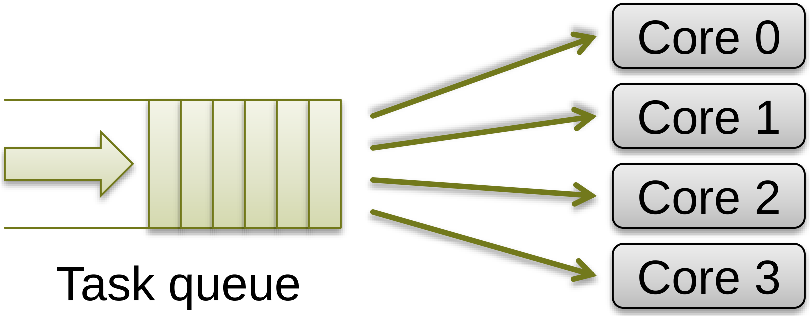
- **Provides a *reservation* scheduler which:**
  - Ensures task gets *s* seconds of time every *p* seconds
  - Approximates weighted fair queuing

- **Algorithm is regularly rediscovered…**

Multiprocessor Scheduling

Challenge 1: sequential programs on multiprocessors

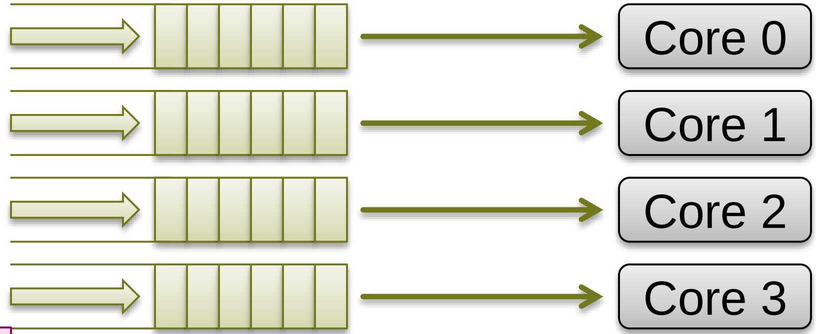
- **Queuing theory ⇒ straightforward, although:**
  - More complex than uniprocessor scheduling
  - Harder to analyze



but…

It’s much harder

- **Overhead of locking and sharing queue**
  - Classic case of scaling bottleneck in OS design
- **Solution: per-processor scheduling queues**



In practice, each is more complex e.g., MFQ

It's much harder

- **Threads allocated arbitrarily to cores**
  - ⇒ tend to move between cores
  - ⇒ tend to move between caches
  - ⇒ really bad locality and hence performance
- **Solution: affinity scheduling**
  - Keep each thread on a core most of the time
  - Periodically rebalance across cores
  - Note: this is often *non-work-conserving!*
- **Alternative: hierarchical scheduling (Linux)**

Challenge 2: parallel applications

- **Global barriers in parallel applications ⇒**
  One slow thread has huge effect on performance
  - Corollary of *Amdahl's Law*
- **Multiple threads would benefit from cache sharing**
- **Different applications pollute each others' caches**
- **Leads to concept of "co-scheduling"**
  - Try to schedule all threads of an application together
- **Critically dependent on *synchronization* concepts**

Multicore scheduling

- **Multiprocessor scheduling is two-dimensional**
  - When to schedule a task?
  - Where (which core) to schedule on?

- **General problem is NP hard ☹**

- **But it's worse than that:**
  - Don't want a process holding a lock to sleep
    ⇒ Might be other running tasks spinning on it
  - Not all cores are equal

- **In general, this is a wide-open research problem**

Little's Law

- **Assume, in a train station:**
  - 100 people arrive per minute
  - Each person spends 15 minutes in the station
  - How big does the station have to be (house how many people)
- **Little's law: "*The average number of active tasks in a system is equal to the average arrival rate multiplied by the average time a task spends in a system*"**

Our Small Quiz

- **True or false (raise hand)**
  - Throughput is an important goal for batch schedulers
  - Response time is an important goal for batch schedulers
  - Realtime schedulers schedule jobs faster than batch schedulers
  - Realtime schedulers have higher throughput than batch schedulers
  - The scheduler has to be invoked by an application
  - FCFS scheduling has low average waiting times
  - Starvation can occur in FCFS scheduling
  - Starvation can occur in SJF scheduling
  - Preemption can be used to improve interactivity
  - Round Robin scheduling is fair
  - Multilevel Feedback Queues in Linux prevent starvation
  - Simple Unix scheduling fairly allocates the time to each user
  - RMS scheduling achieves full CPU utilization
  - Multiprocessor scheduling is NP hard

Last time: Scheduling

- **Basics:**
  - Workloads, tradeoffs, definitions
- **Batch-oriented scheduling**
  - FCFS, Convoys, SJF, Preemption: SRTF
- **Interactive workloads**
  - RR, Priority, Multilevel Feedback Queues, Linux, Resource containers
- **Realtime**
  - RMS, EDF
- **Multiprocessors**

- **This time: OSPP Section 5 (not including IPC)**

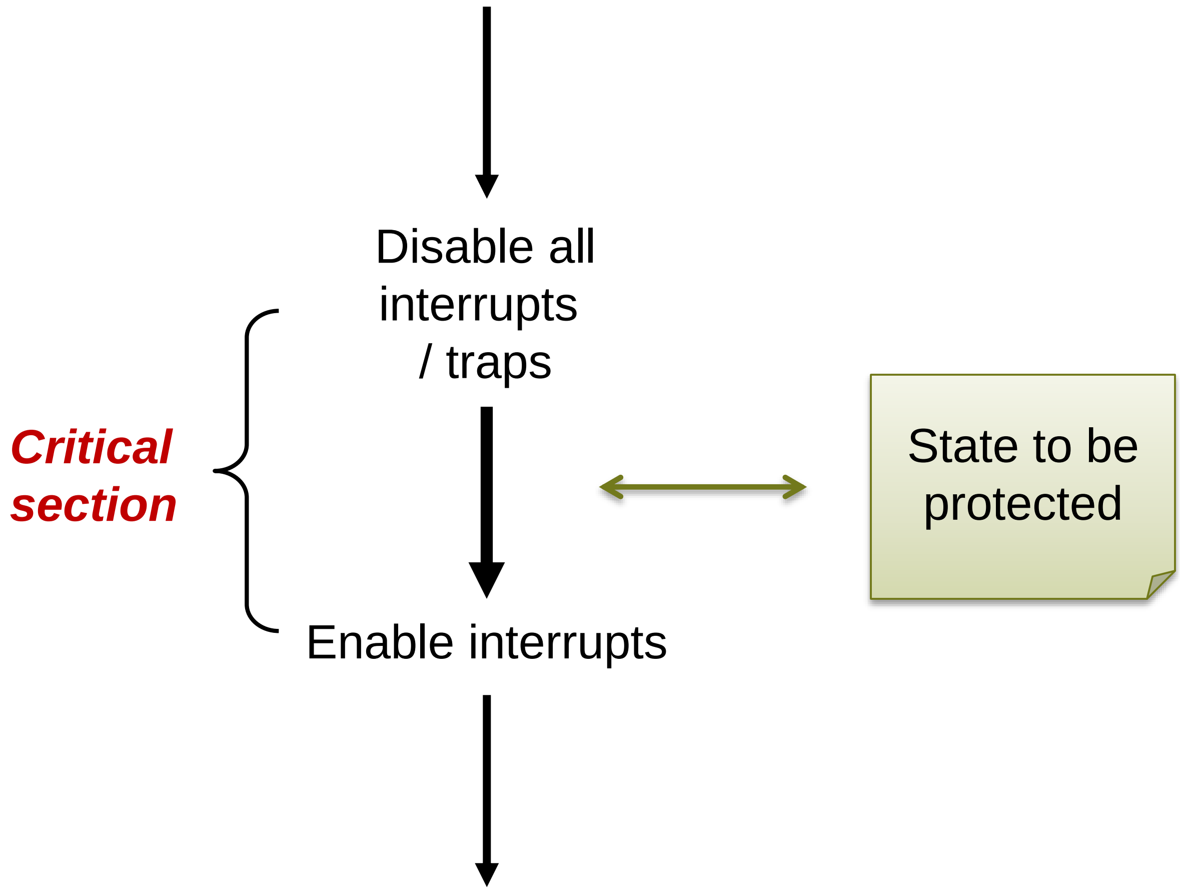
Goals today

- **Overview of inter-process communication systems**
  - Hardware support
  - With shared memory
  - Without shared memory
  - Upcalls

- **Generally: very broad field**
  - Quite competitive… especially with microkernels

Recap: Hardware support for synchronization

Disabling interrupts



Disabling interrupts

- **Nice and simple**
- **Can't be rescheduled inside critical section**
  ⇒ data can't be altered by anything else
- **Except…**
- **Another processor!**
  - Hmm….

- **Very efficient** **if** **in kernel on a** ***uniprocessor*****.**

Test-And-Set instruction

- **Atomically:**
  - Read the value of a memory location
  - Set the location to 1 (or another constant)

- **Available on some hardware (e.g., PA-RISC)**
  - (actually, more a RAC – Read-And-Clear)

Compare-And-Swap (CAS)

```
word cas(word *flag, word oldval, word newval) {
        atomically {
                if (*flag == oldval) {
                        *flag = newval;
                        return oldval;
                } else {
                        return *flag;
                }
        }
}
```

- **Available on e.g., x86, IBM/370, SPARC, ARM,…**
- **Theoretically, *slightly* more powerful than TAS**
  - Why?
  - Other variants e.g., CAS2, etc.

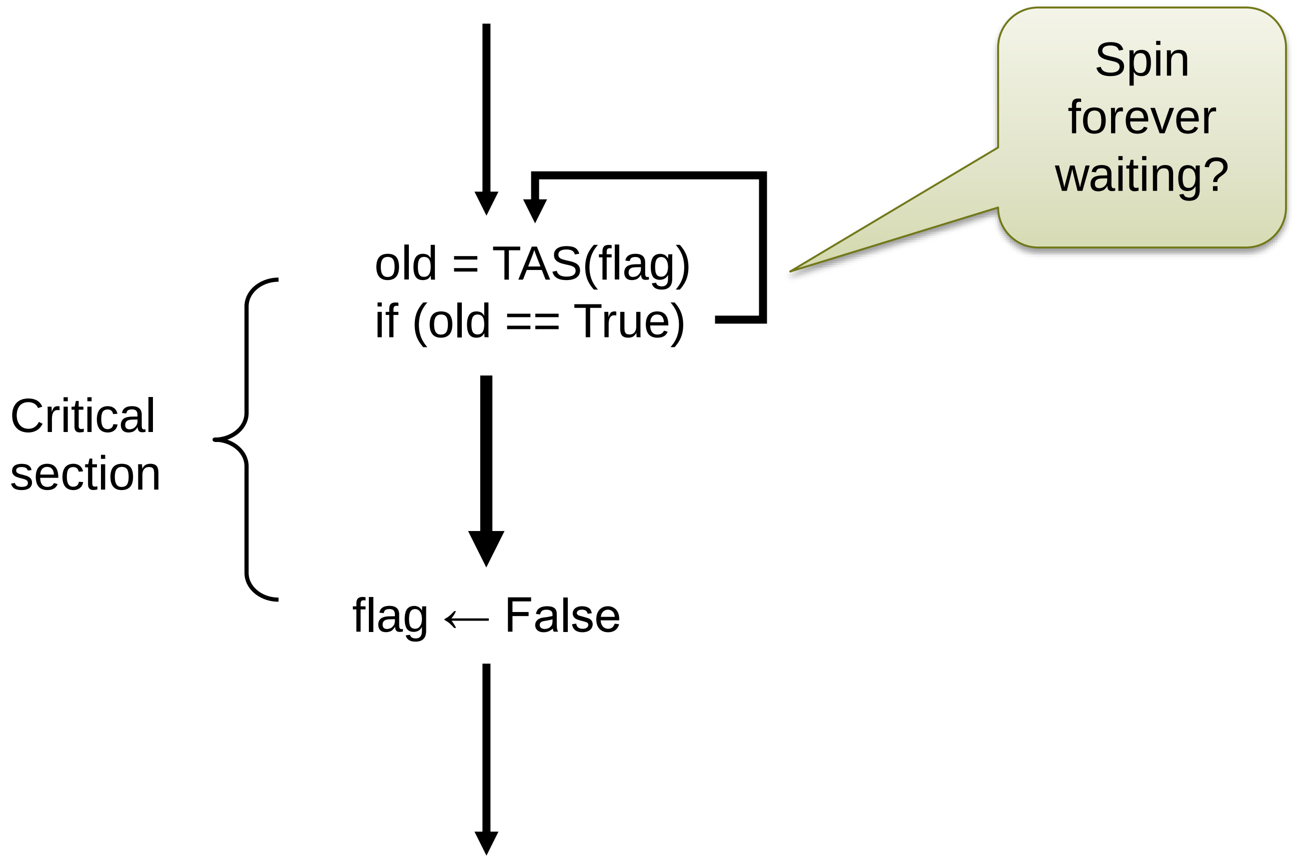
Load-Link, Store-Conditional

Factors `CAS`, etc. into two instructions:

1. **`LL`: load from a location and mark as "owned"**
2. **`SC`: Atomically:**
   1. Store *only* if already marked by this processor
   2. Clear any marks set by other processors
   3. Return whether it worked.

Available on PPC, Alpha, MIPS, etc…

Back to TAS…


Spin forever waiting?
old = TAS(flag)
if (old == True)
Critical section
flag ← False

Spinning

- **On a uniprocessor:**
  - Not much point in spinning at all. What's going to happen?
  - Possibly an interrupt

- **On a multiprocessor:**
  - Can't spin forever
  - Another spin is always cheap
  - Blocking thread and rescheduling is expensive
  - Spinning only works if lock holder is running on another core

Competitive spinning

- **How long to spin for?**

- **"Competitive spinning":**
  - Within a factor of 2 of optimal, offline (i.e., impossible!) algorithm

- **Good approach: spin for the context switch time**
  - Best case: avoid context switch entirely
  - Worst case: twice as bad as simply rescheduling

IPC with shared memory

Techniques you already know ☺

- **Semaphores**
  - P, V operations

- **Mutexes**
  - Acquire, Release

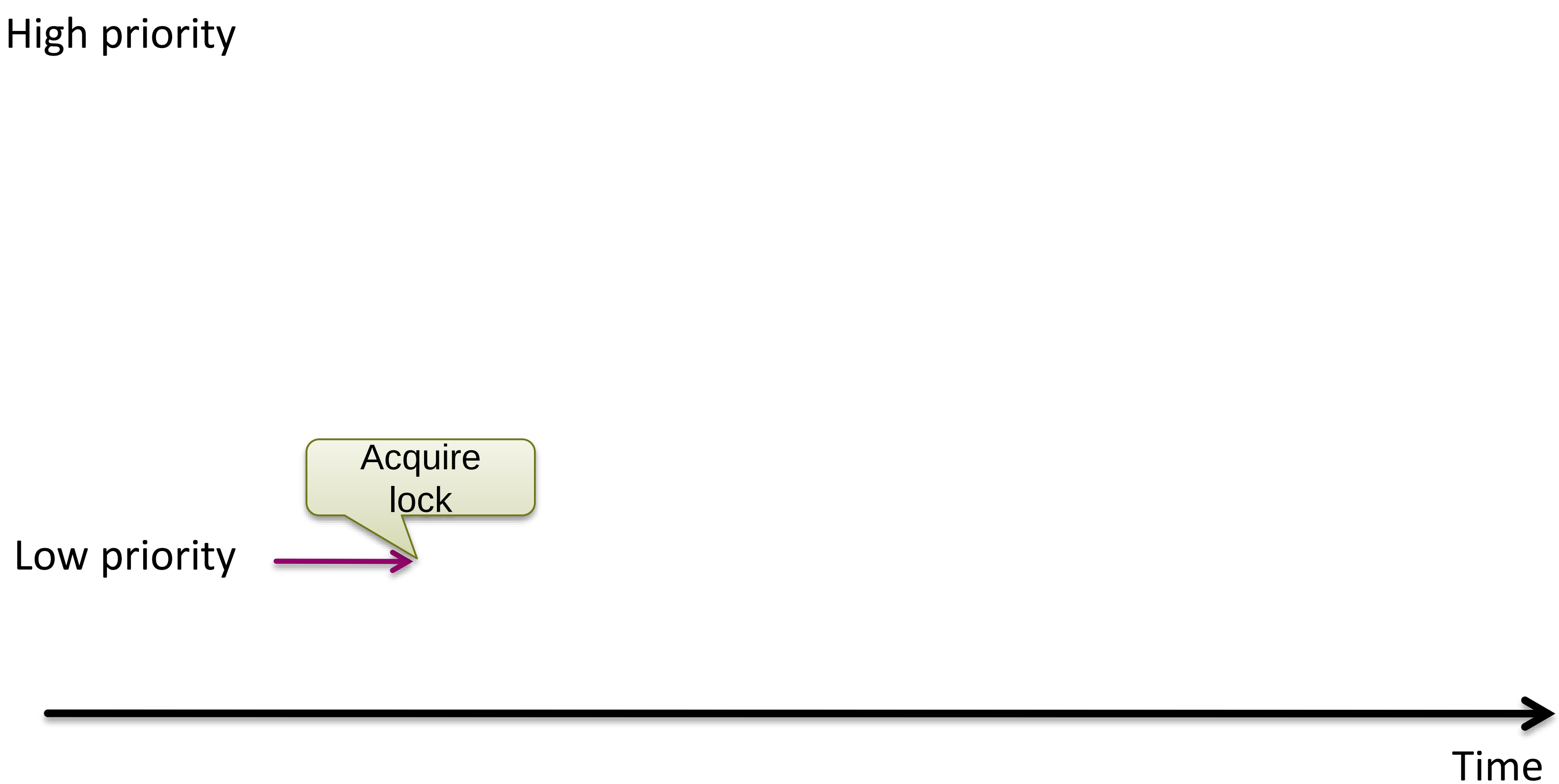
- **Condition Variables**
  - Wait, Signal (Notify), Broadcast (NotifyAll)

- **Monitors**
  - Enter, Exit

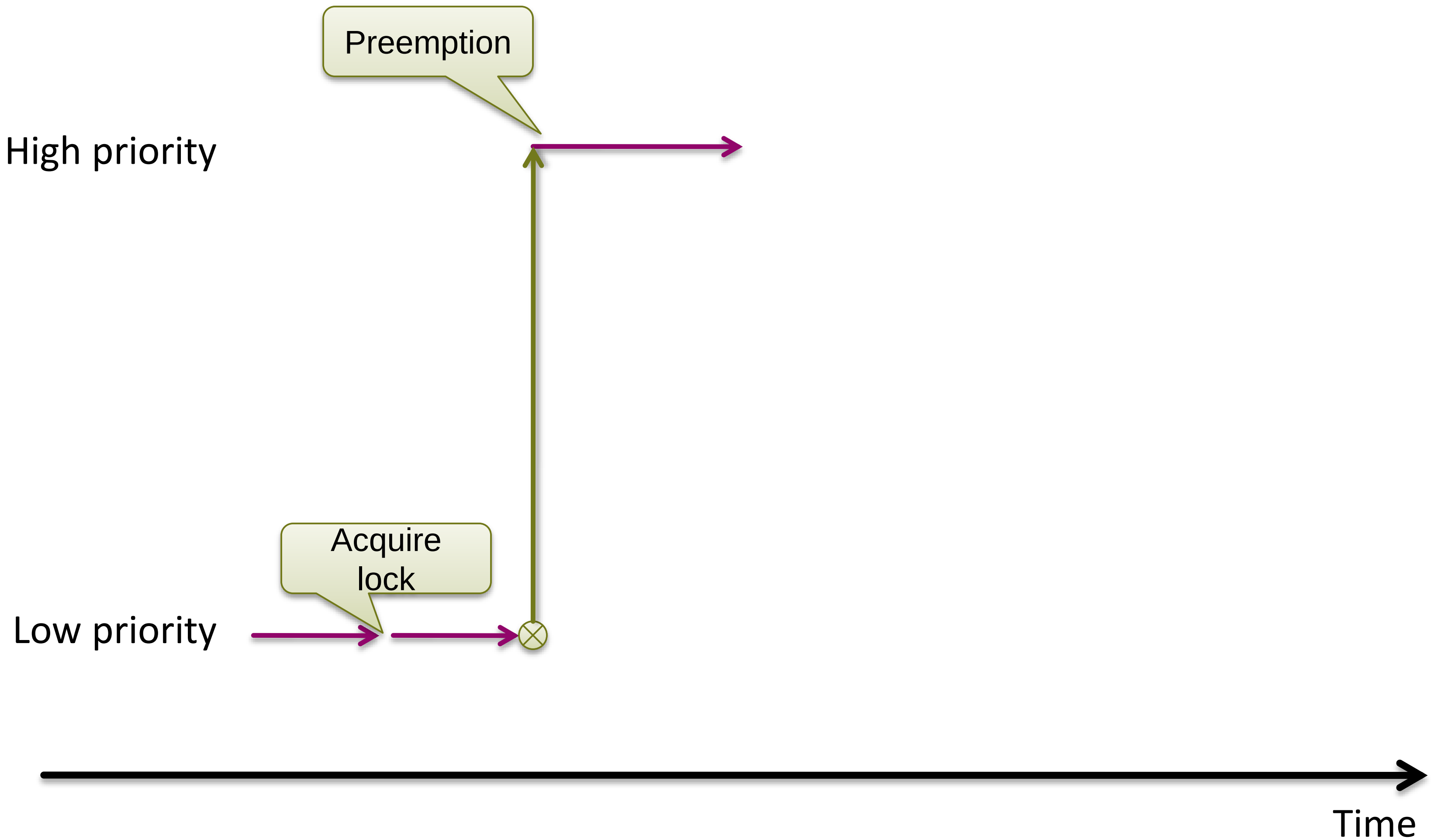
Focus here: interaction with scheduling

- **Most OSes provide some form of these**
- **Key issue not yet covered: interaction between scheduling and synchronization**
- **Example: Priority inversion**
  - Assuming a priority scheduler, e.g., Unix, Windows

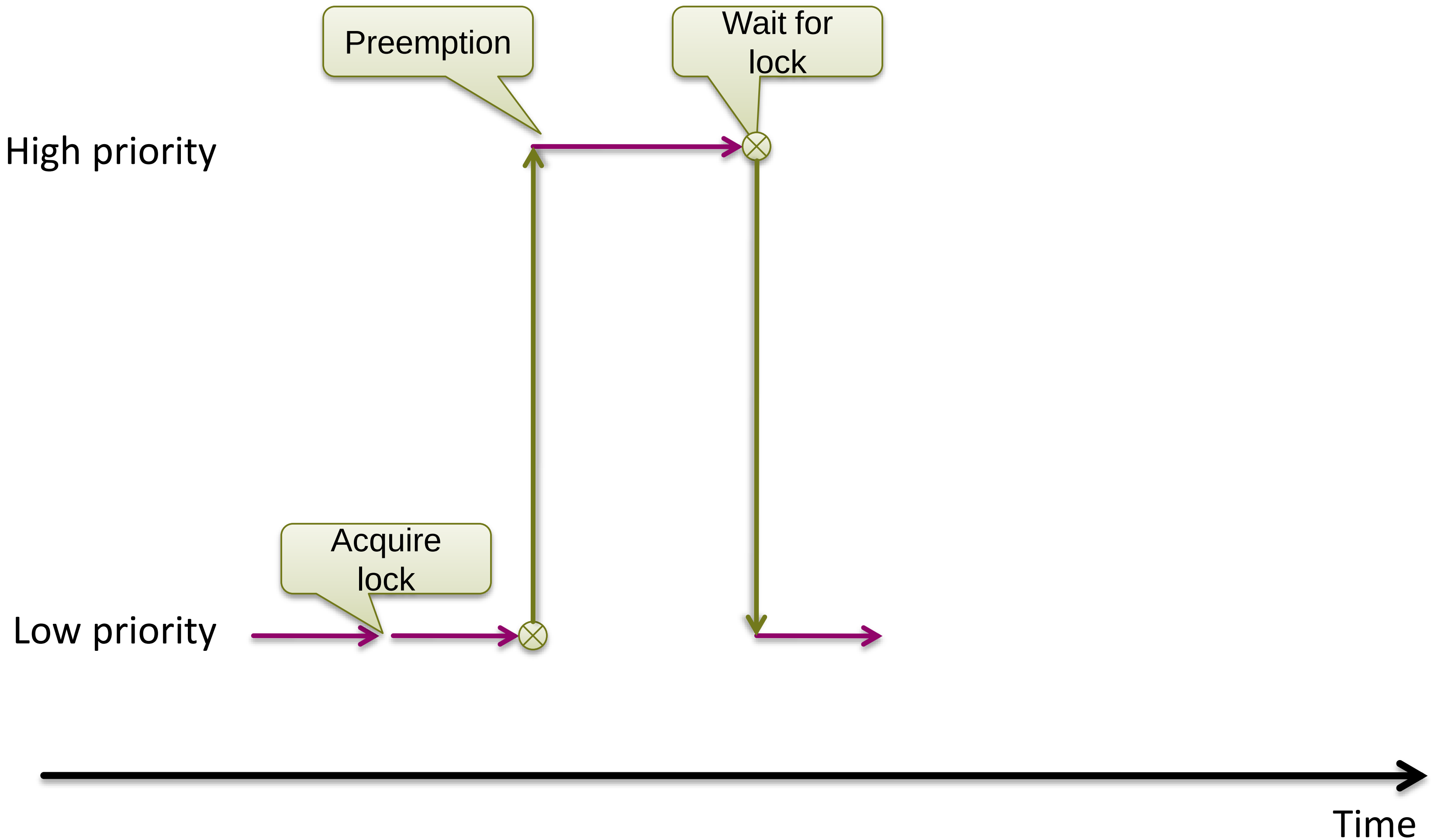
Priority Inversion



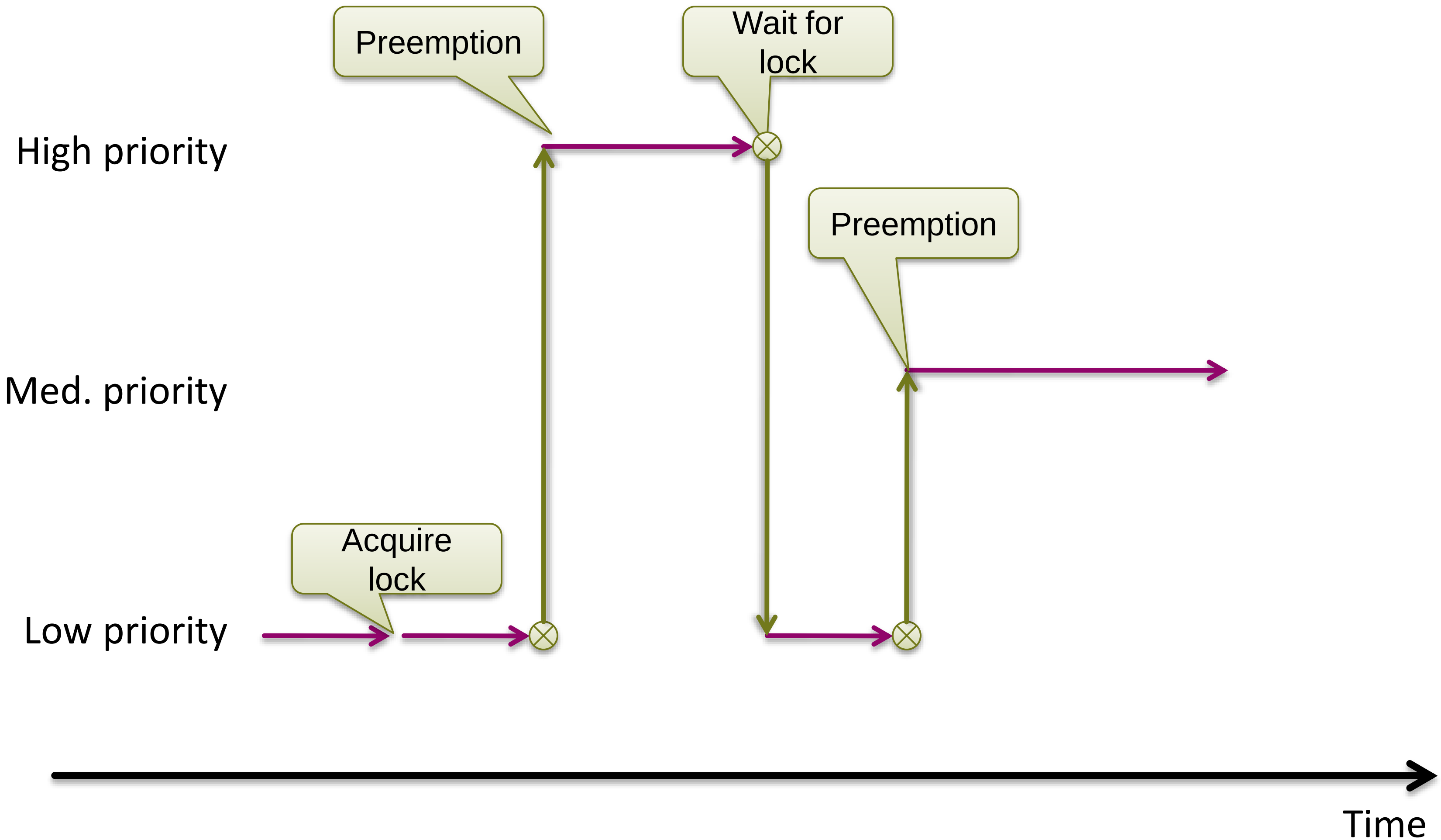
Priority Inversion



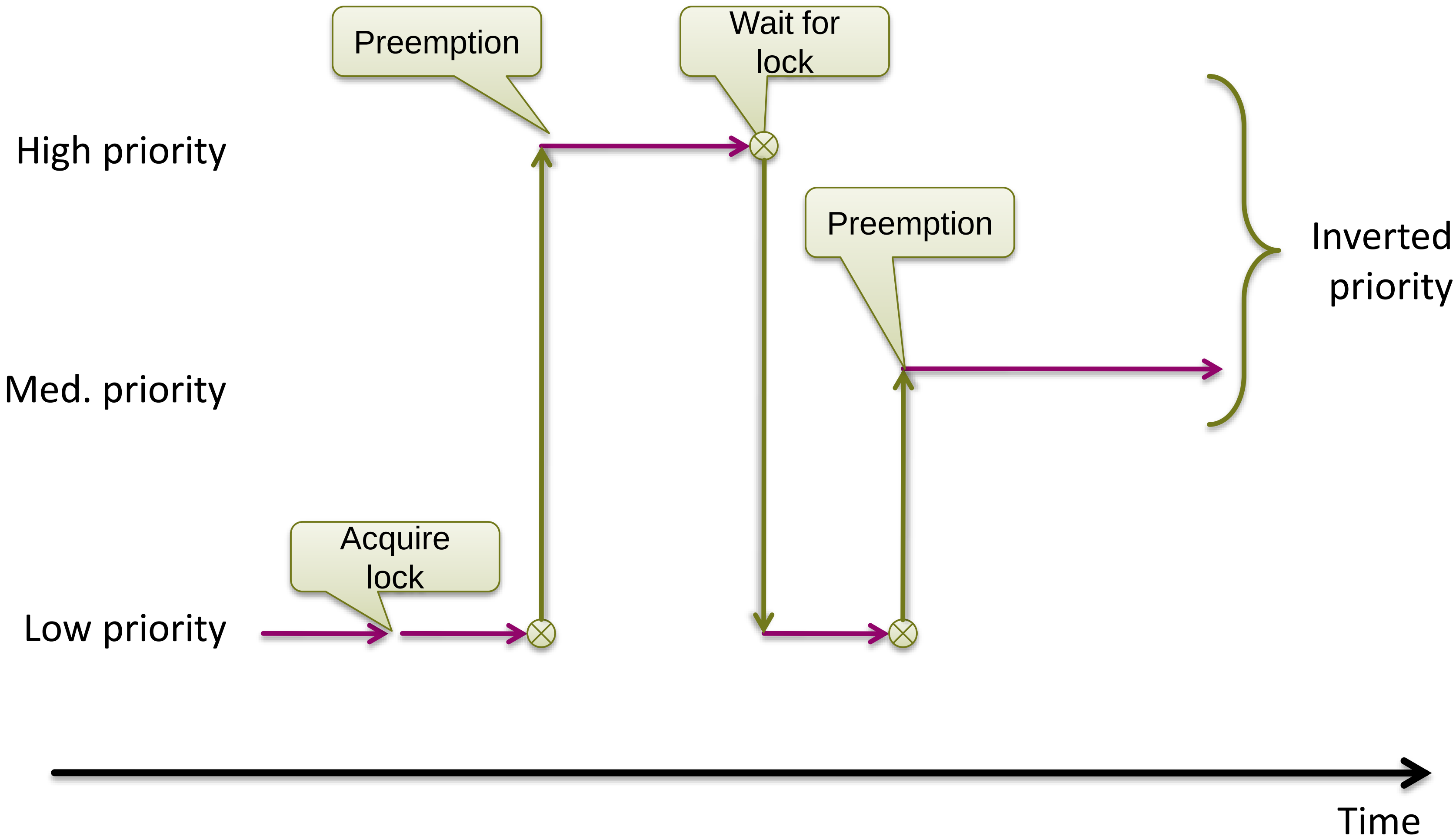
Priority Inversion



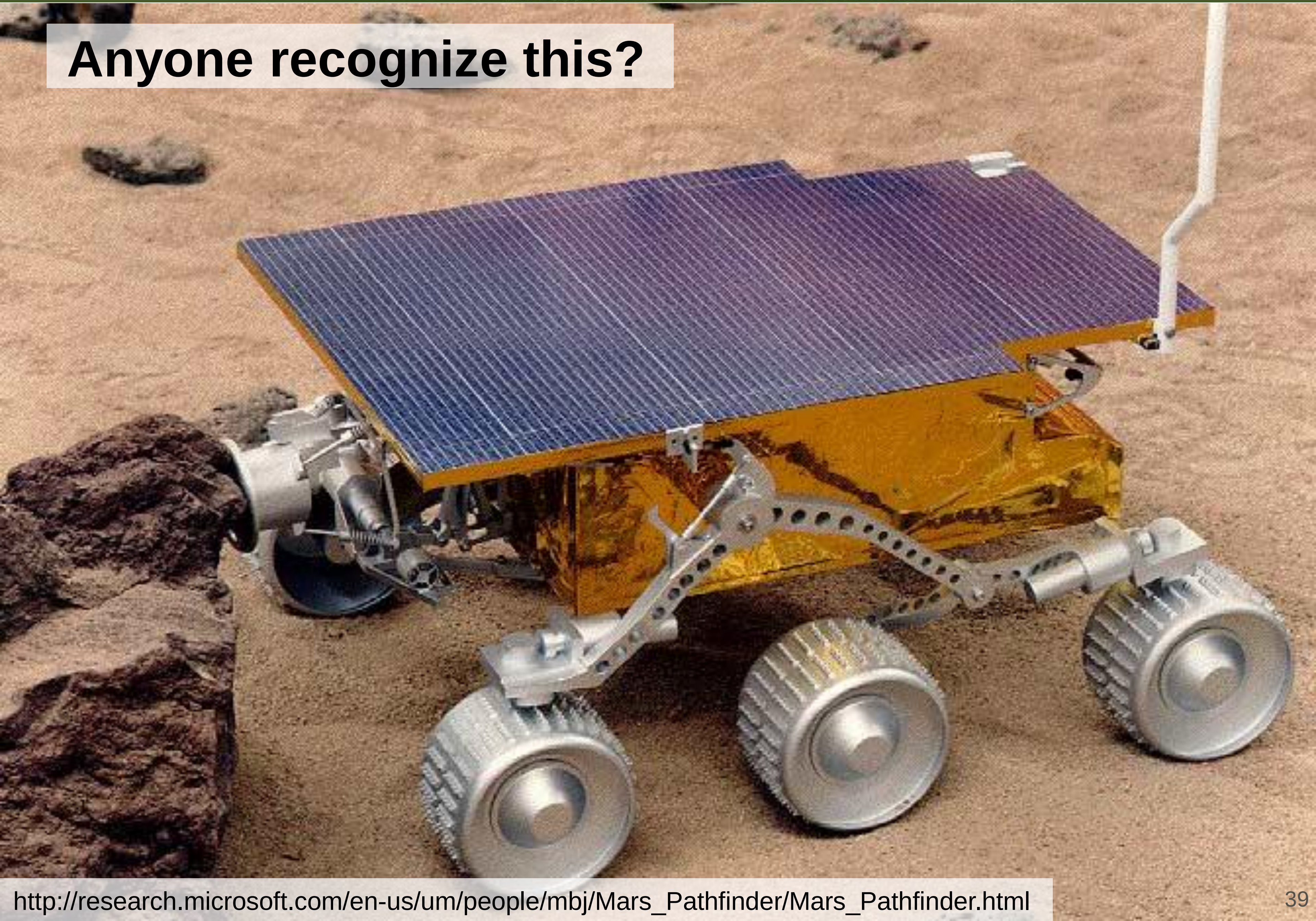
Priority Inversion



Priority Inversion



Anyone recognize this?



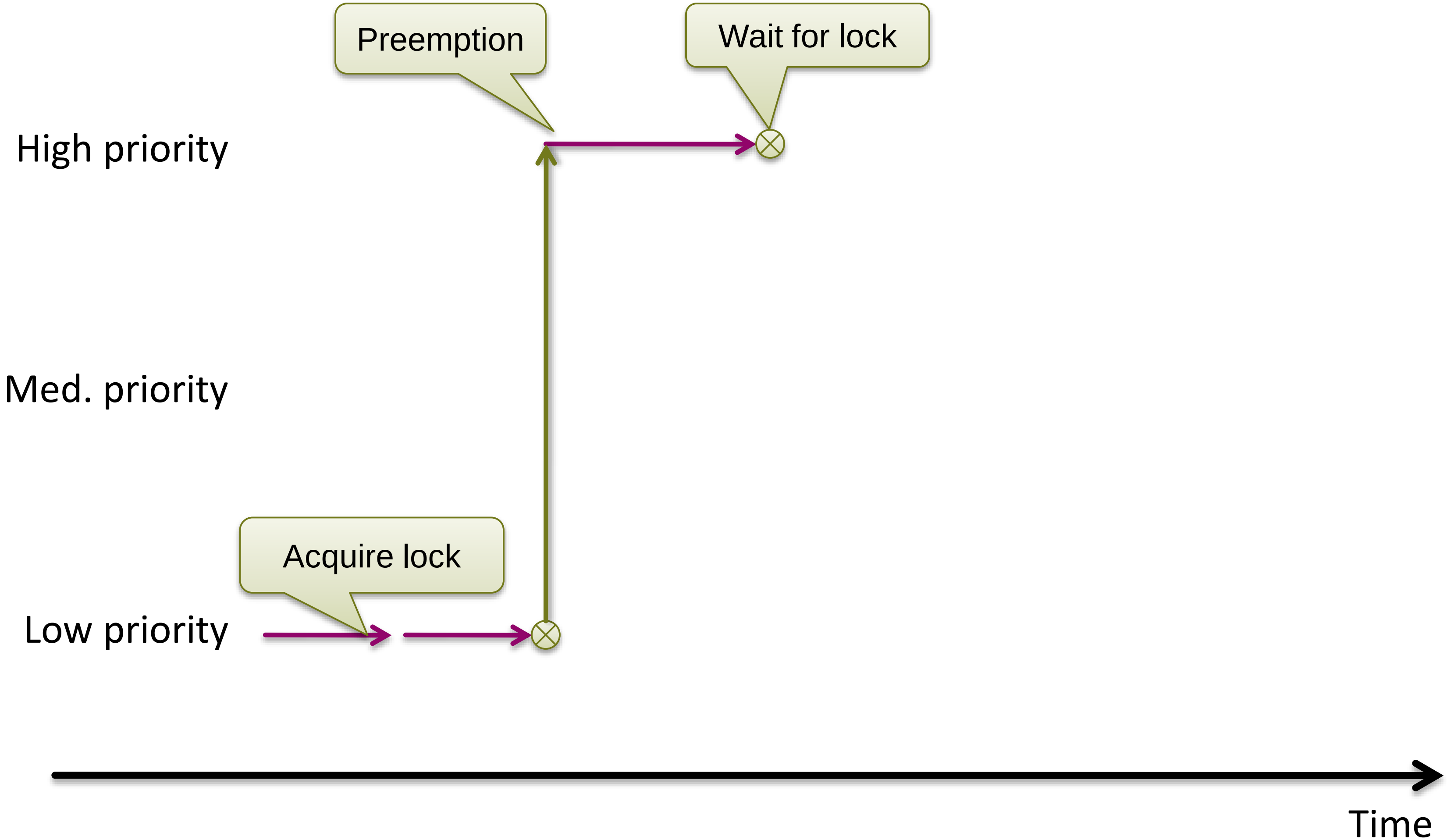
http://research.microsoft.com/en-us/um/people/mbj/Mars_Pathfinder/Mars_Pathfinder.html

Priority Inheritance

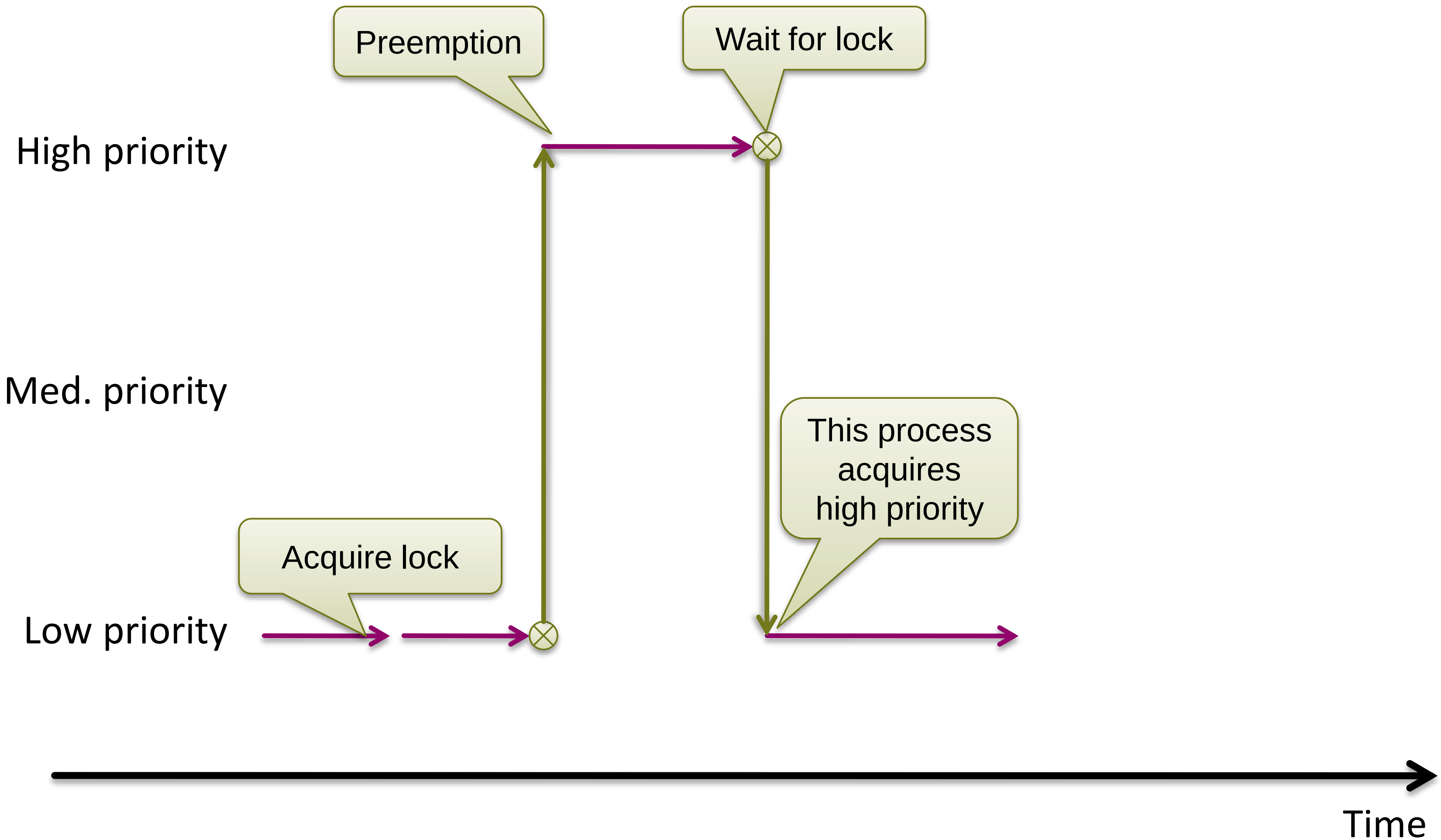
- **Process holding lock *inherits* priority of highest priority process that is waiting for the lock.**
  - Releasing lock $\Rightarrow$ priority returns to previous value
  - Ensures forward progress

- **Alternative: *Priority Ceiling***
  - Process holding lock acquires priority of highest-priority process that *can ever* hold lock
  - Requires static analysis, used in embedded RT systems

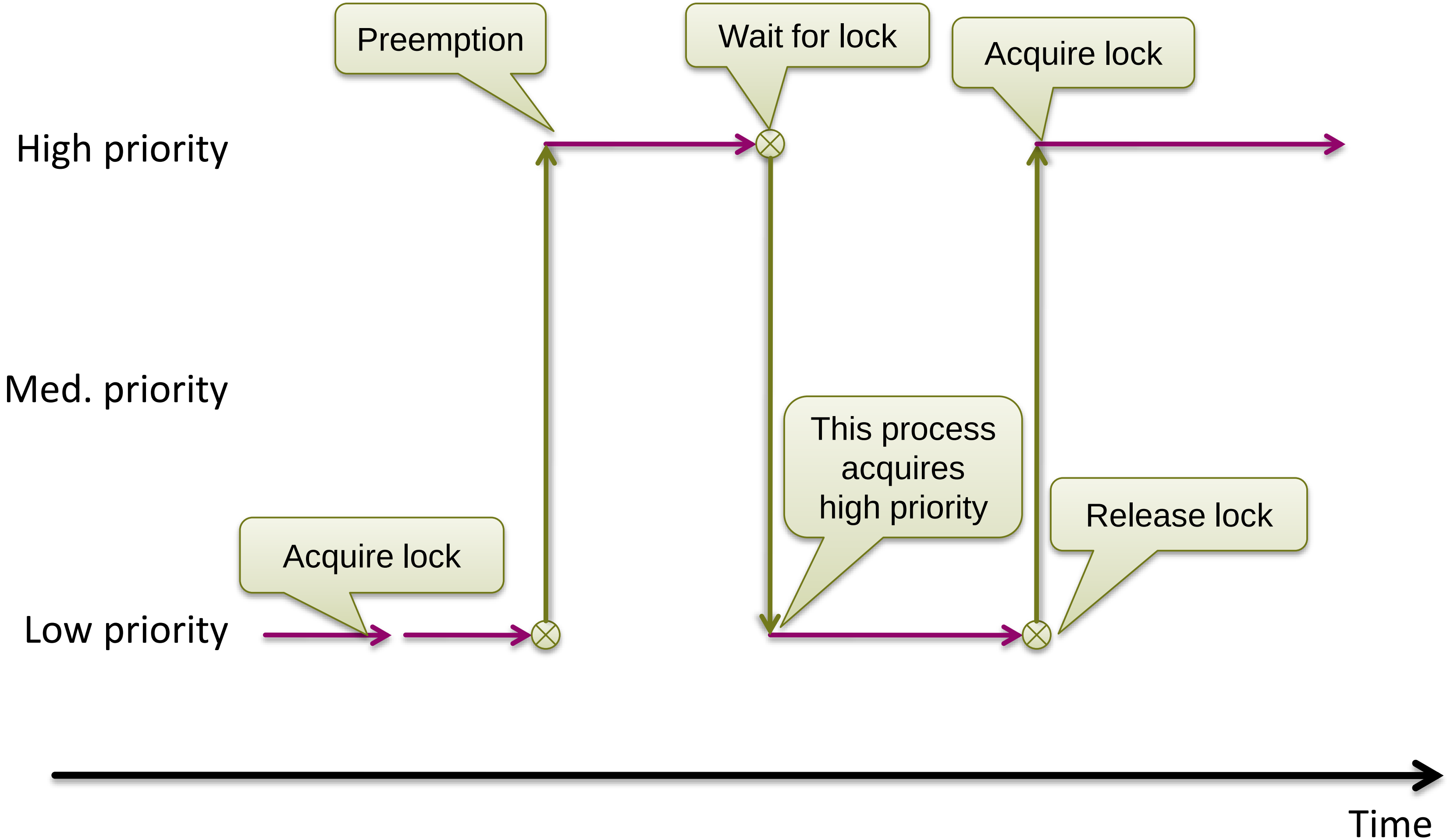
Priority Inheritance



Priority Inheritance

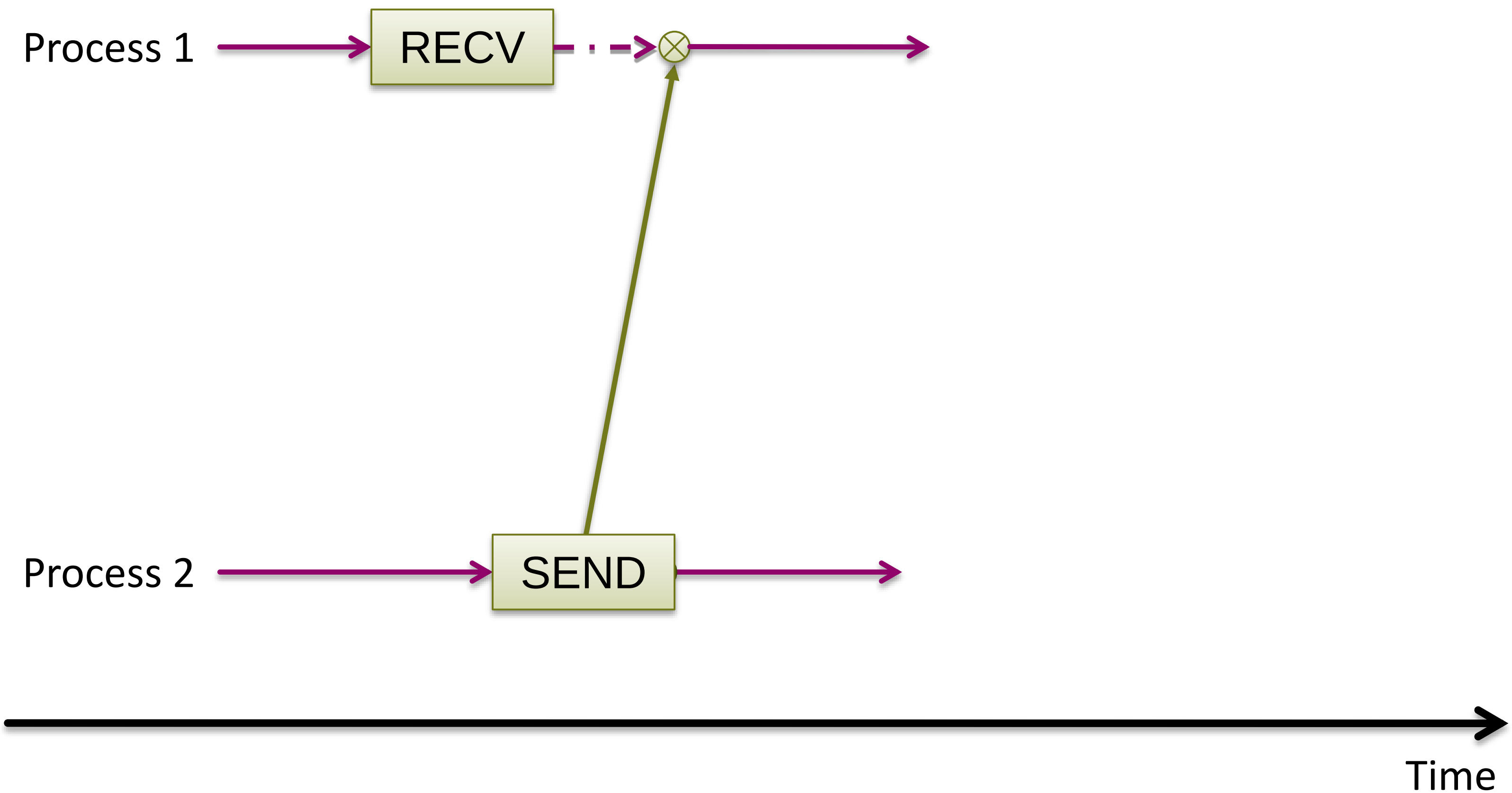


Priority Inheritance

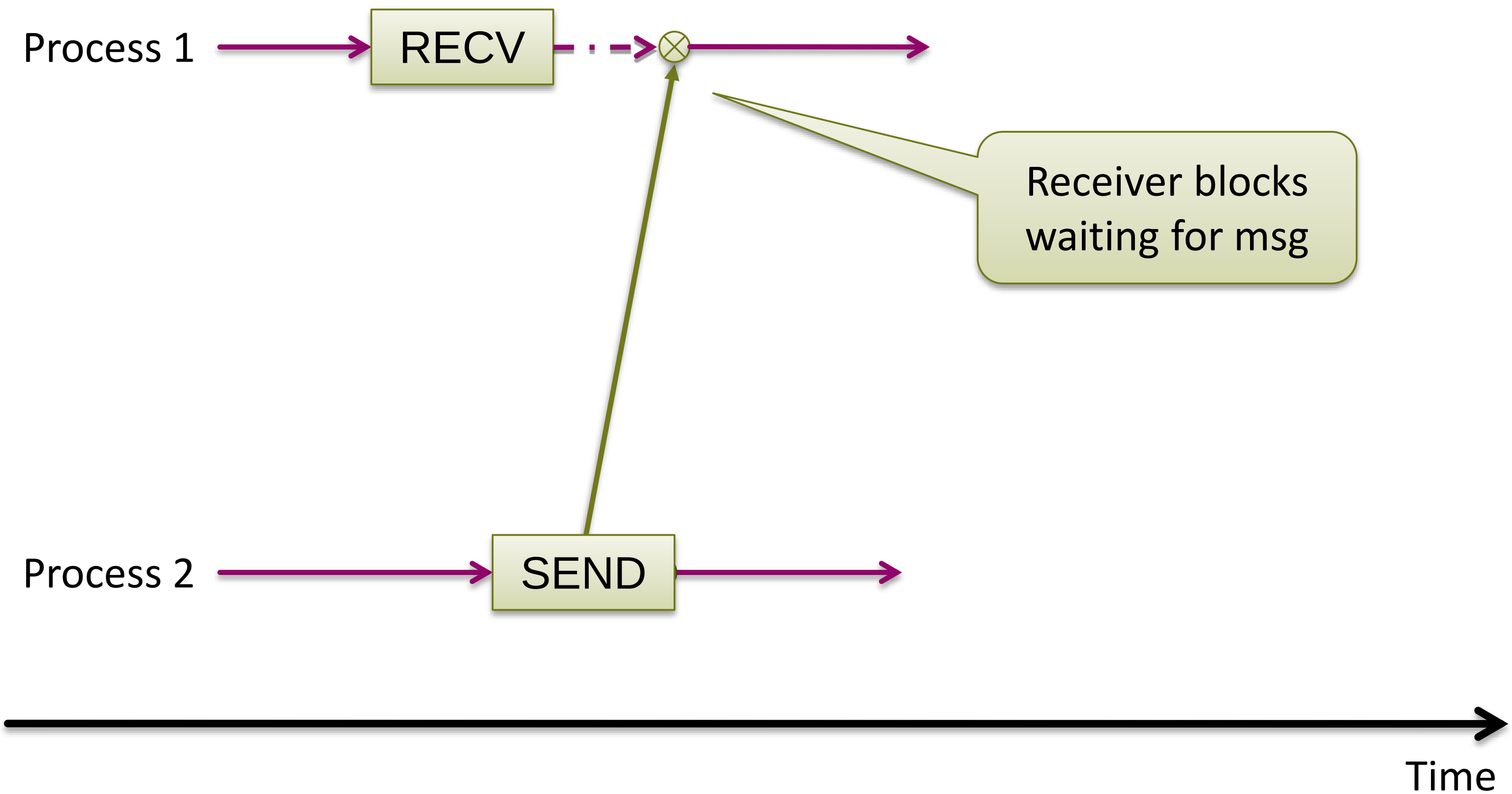


IPC without shared memory

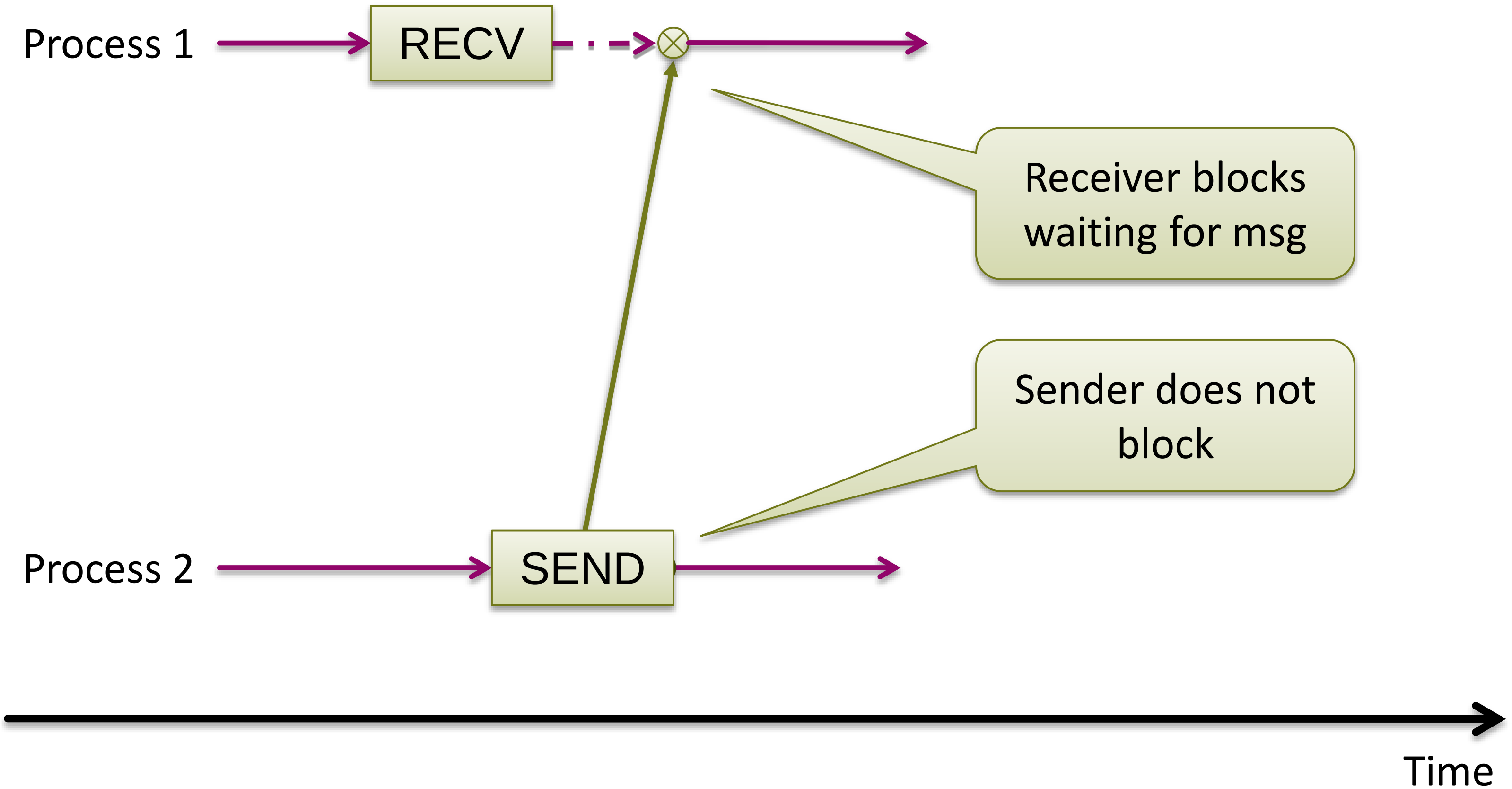
Asynchronous (buffered) IPC



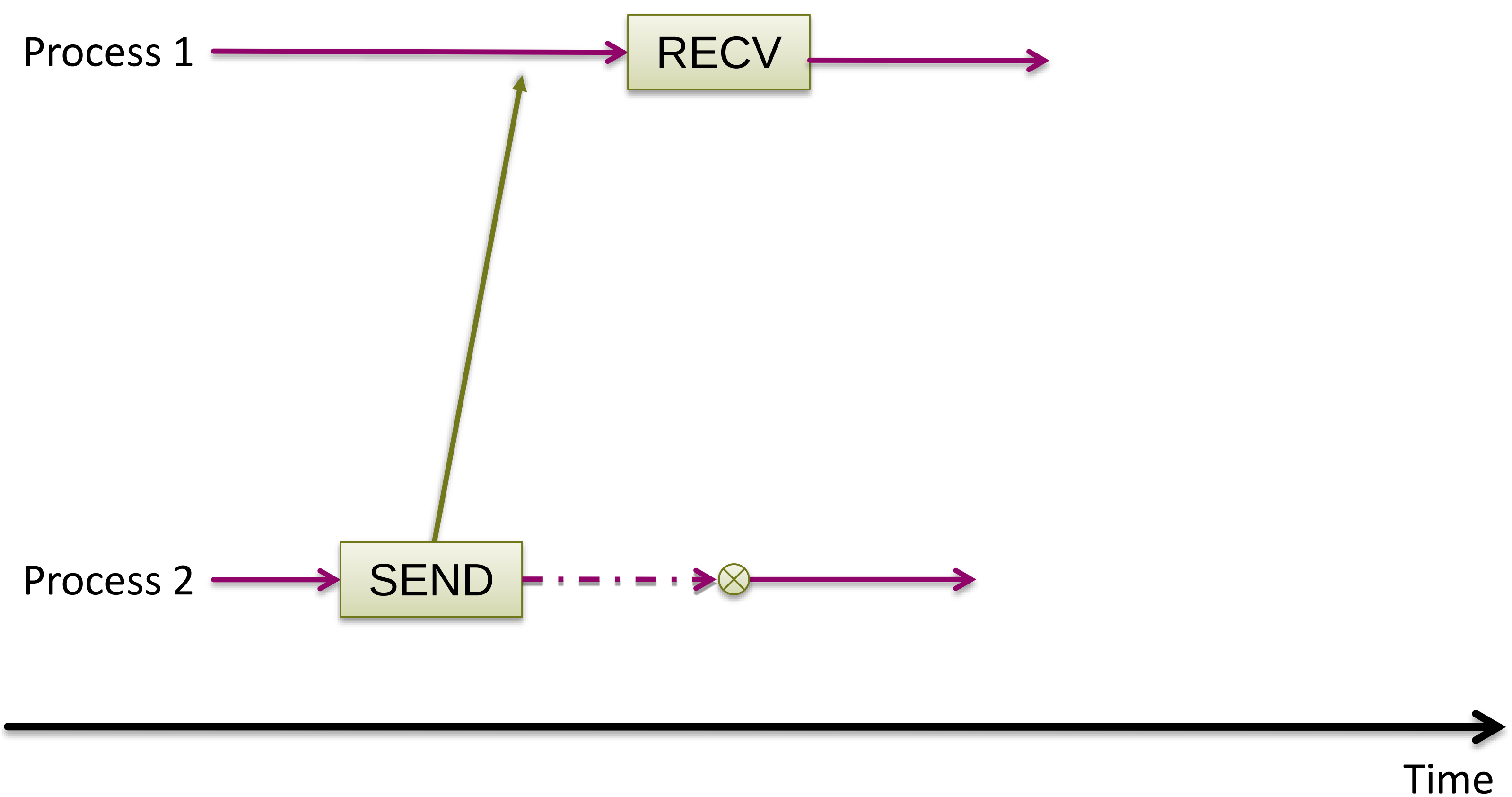
Asynchronous (buffered) IPC



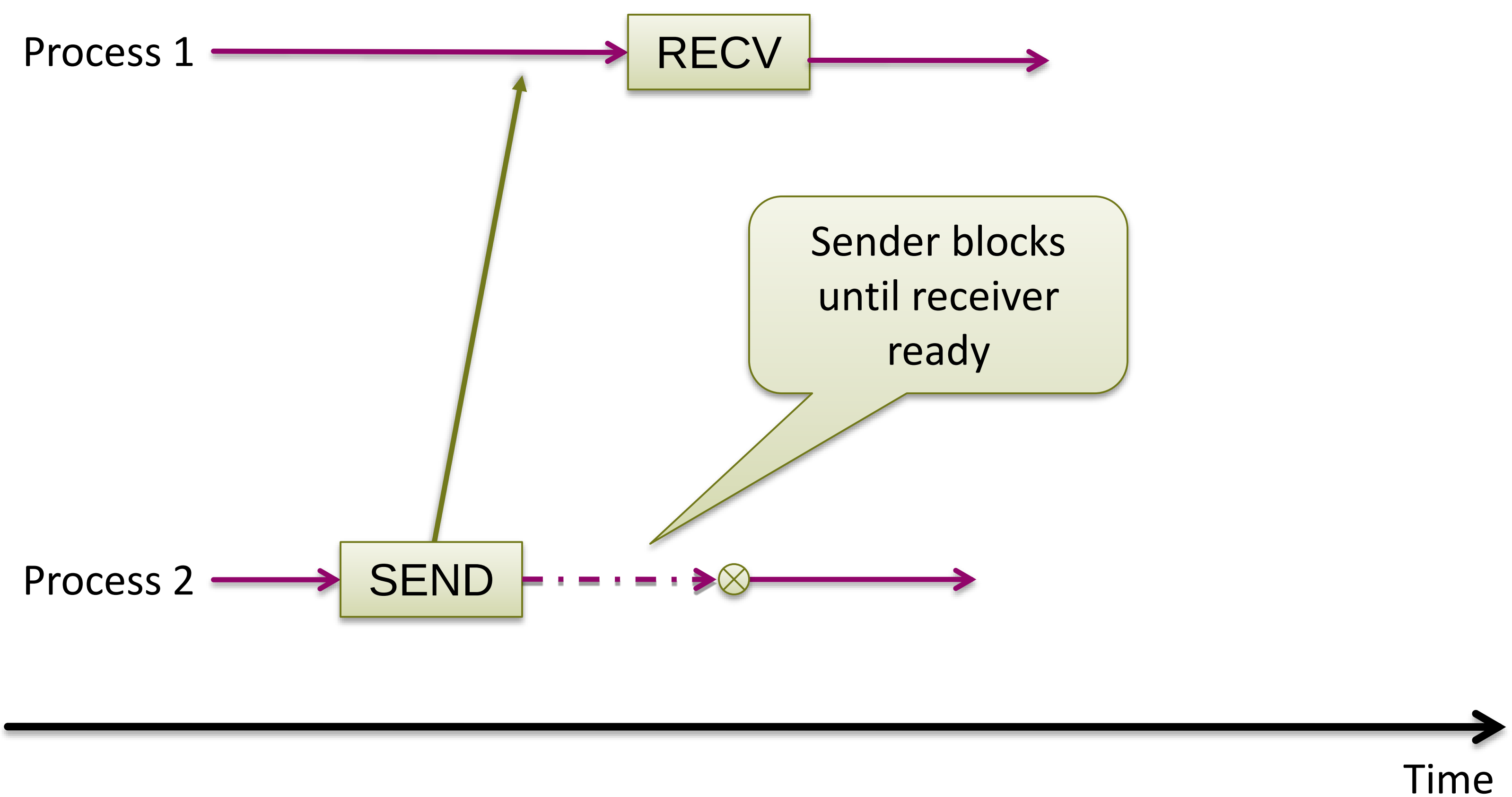
Asynchronous (buffered) IPC



Synchronous (unbuffered) IPC



Synchronous (unbuffered) IPC



Duality of messages and shared-memory

- **Famous claim by Lauer and Needham (1978):**

Any shared-memory system (e.g., one based on monitors and condition variables) is equivalent to a non-shared-memory system (based on messages)

- **Exercise: pick your favourite example of one, and show how to build the dual.**

Unix Pipes

- Basic (first) Unix IPC mechanism
- Unidirectional, buffered communication channel between two processes
- Creation:

```
int pipe(int pipefd[2])
```

- Q. How to set up pipe between two processes?
- A. Don't! Create the pipe first, then fork…

Pipe idiom (man 2 pipe)

```
int
main(int argc, char *argv[])
{
    int pipefd[2];
    pid_t cpid;
    char buf;

    assert(argc == 2);

    if (pipe(pipefd) == -1) {
        perror("pipe");
        exit(EXIT_FAILURE);
    }

    cpid = fork();
    if (cpid == -1) {
        perror("fork");
        exit(EXIT_FAILURE);
    }

    if (cpid == 0) {    /* Child reads from pipe */
        close(pipefd[1]);          /* Close unused write end */

        while (read(pipefd[0], &buf, 1) > 0)
            write(STDOUT_FILENO, &buf, 1);

        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        _exit(EXIT_SUCCESS);

    } else {            /* Parent writes argv[1] to pipe */
        close(pipefd[0]);          /* Close unused read end */
        write(pipefd[1], argv[1], strlen(argv[1]));
        close(pipefd[1]);          /* Reader will see EOF */
        wait(NULL);                /* Wait for child */
        exit(EXIT_SUCCESS);
    }
}
```

Create a pipe

Pipe idiom (man 2 pipe)

```
int
main(int argc, char *argv[])
{
    int pipefd[2];
    pid_t cpid;
    char buf;

    assert(argc == 2);

    if (pipe(pipefd) == -1) {
        perror("pipe");
        exit(EXIT_FAILURE);
    }

    cpid = fork();
    if (cpid == -1) {
        perror("fork");
        exit(EXIT_FAILURE);
    }

    if (cpid == 0) {    /* Child reads from pipe */
        close(pipefd[1]);          /* Close unused write end */

        while (read(pipefd[0], &buf, 1) > 0)
            write(STDOUT_FILENO, &buf, 1);

        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        _exit(EXIT_SUCCESS);

    } else {            /* Parent writes argv[1] to pipe */
        close(pipefd[0]);          /* Close unused read end */
        write(pipefd[1], argv[1], strlen(argv[1]));
        close(pipefd[1]);          /* Reader will see EOF */
        wait(NULL);                /* Wait for child */
        exit(EXIT_SUCCESS);
    }
}
```

Fork

Pipe idiom (man 2 pipe)

```
int
main(int argc, char *argv[])
{
    int pipefd[2];
    pid_t cpid;
    char buf;

    assert(argc == 2);

    if (pipe(pipefd) == -1) {
        perror("pipe");
        exit(EXIT_FAILURE);
    }

    cpid = fork();
    if (cpid == -1) {
        perror("fork");
        exit(EXIT_FAILURE);
    }

    if (cpid == 0) {    /* Child reads from pipe */
        close(pipefd[1]);          /* Close unused write end */

        while (read(pipefd[0], &buf, 1) > 0)
            write(STDOUT_FILENO, &buf, 1);

        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        _exit(EXIT_SUCCESS);

    } else {            /* Parent writes argv[1] to pipe */
        close(pipefd[0]);          /* Close unused read end */
        write(pipefd[1], argv[1], strlen(argv[1]));
        close(pipefd[1]);          /* Reader will see EOF */
        wait(NULL);                /* Wait for child */
        exit(EXIT_SUCCESS);
    }
}
```

In child: close write end

Pipe idiom (man 2 pipe)

```
int
main(int argc, char *argv[])
{
    int pipefd[2];
    pid_t cpid;
    char buf;

    assert(argc == 2);

    if (pipe(pipefd) == -1) {
        perror("pipe");
        exit(EXIT_FAILURE);
    }

    cpid = fork();
    if (cpid == -1) {
        perror("fork");
        exit(EXIT_FAILURE);
    }

    if (cpid == 0) {    /* Child reads from pipe */
        close(pipefd[1]);          /* Close unused write end */

        while (read(pipefd[0], &buf, 1) > 0)
            write(STDOUT_FILENO, &buf, 1);

        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        _exit(EXIT_SUCCESS);

    } else {            /* Parent writes argv[1] to pipe */
        close(pipefd[0]);          /* Close unused read end */
        write(pipefd[1], argv[1], strlen(argv[1]));
        close(pipefd[1]);          /* Reader will see EOF */
        wait(NULL);                /* Wait for child */
        exit(EXIT_SUCCESS);
    }
}
```

Read from pipe and write to standard output until EOF

Pipe idiom (man 2 pipe)

```
int
main(int argc, char *argv[])
{
    int pipefd[2];
    pid_t cpid;
    char buf;

    assert(argc == 2);

    if (pipe(pipefd) == -1) {
        perror("pipe");
        exit(EXIT_FAILURE);
    }

    cpid = fork();
    if (cpid == -1) {
        perror("fork");
        exit(EXIT_FAILURE);
    }

    if (cpid == 0) {    /* Child reads from pipe */
        close(pipefd[1]);          /* Close unused write end */

        while (read(pipefd[0], &buf, 1) > 0)
            write(STDOUT_FILENO, &buf, 1);

        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        _exit(EXIT_SUCCESS);

    } else {            /* Parent writes argv[1] to pipe */
        close(pipefd[0]);          /* Close unused read end */
        write(pipefd[1], argv[1], strlen(argv[1]));
        close(pipefd[1]);          /* Reader will see EOF */
        wait(NULL);                /* Wait for child */
        exit(EXIT_SUCCESS);
    }
}
```

In parent: close read end and write argv[1] to pipe

Unix shell pipes

- **E.g.:**

```
curl --silent http://spcl.inf.ethz.ch/Teaching/2015-osnet/ | sed
   's/[^A-Za-z]/\n/g' | sort -fu | egrep -v '^\s*$' | wc -l
```

- **Shell forks each element of the pipeline**
  - Each process connected via pipes
  - Stdout of process *n* → stdin of process *n+1*
  - Each process then exec's the appropriate command
  - Exercise: write it! (hint: 'man dup2'…)

Messaging systems

- **A good textbook will examine options:**
  - End-points may or may not know each others' names
  - Messages might need to be sent to more than one destination
  - Multiple arriving messages might need to be demultiplexed
  - Can't wait forever for one particular message

- **BUT: you'll see most of this somewhere else!**
  - In networking
  - Many parallels between message-passing operating systems and networks

Example

- **The concept of a "port" allows:**
  - Naming of different end-points within a process
  - Demultiplexing of messages
  - Waiting selectively for different kinds of messages

- **Analogous to "socket" and "TCP port" in IPv4**
  - In Unix, "Unix domain sockets" do exactly this.
  - `int s = socket(AF_UNIX, type, 0);`

Naming pipes

- **Pipes so far are only named by their descriptors**
  - Namespace is *local* to the process
  - Copied on **`fork()`**

- **How to put a pipe in the global namespace?**
  - Make it a “named pipe”
  - Special file of type “pipe” (also known as a FIFO)

Named pipes

htor@lenny: ~

```
htor@lenny:~$ mkfifo /tmp/fifo
htor@lenny:~$ echo "Hello" > /tmp/fifo
htor@lenny:~$
```

htor@lenny: ~

```
htor@lenny:~$ cat /tmp/fifo
Hello
htor@lenny:~$
```

Local Remote Procedure Call

- **Can use RPC locally:**
  - Define procedural interface in an IDL
  - Compile / link stubs
  - Transparent procedure calls over messages

- **Naïve implementation is slow**
  - Lots of things (like copying) don't matter with a network, but do matter between local processes
  - Can be made very fast: more in the AOS course…

Unix signals

- ***Asynchronous*** **notification from the kernel**
- **Receiver doesn't wait: signal just happens**
- **Interrupt process, and:**
  - Kill it
  - Stop (freeze) it
  - Do "something else" (see later)

Signal types (some of them)

Name	Description / meaning	Default action
SIGHUP	Hangup / death of controlling process	Terminate process
SIGINT	Interrupt character typed (CTRL-C)	e process
SIGQUIT	Quit character typed (CTRL-\)	Core dump
SIGKILL	**kill -9 <process id>**	**Terminate process**
SIGSEGV	Segfault (invalid memory reference	lump
SIGPIPE	Write on pipe with no reader	Terminate process
SIGALRM	**alarm()** goes off	minate process
SIGCHLD	Child process stopped or terminated	Ignored
SIGSTOP	Stop process	Stop
SIGCONT	Continue process	
SIGUSR1,2	User-defined signals	Terminate process

"Hanging up" the phone (terminal)

Can't be disabled!

E.g., after other side of pipe has closed it

Used by debuggers (e.g., **gdb**) and shell (**CTRL-Z**)

Etc. – see **man 7 signal** for the full list

Where do signals come from?

- **Memory management subsystem:**
  - **`SIGSEGV`**, etc.

- **IPC system**
  - **`SIGPIPE`**

- **Other user processes**
  - **`SIGUSR1,2`**, **`SIGKILL`**, **`SIGSTOP`**, **`SIGCONT`**

- **Kernel trap handlers**
  - **`SIGFPE`**

- **The "TTY Subsystem"**
  - **`SIGINT`**, **`SIGQUIT`**, **`SIGHUP`**

Sending a signal to a process

- From the Unix shell:

```
$ kill –HUP 4234
```

- From C:

```
#include <signal.h>
int kill(pid_t pid, int signo);
```

- “Kill” is a rather unfortunate name ☹

Unix signal handlers

- **Change what happens when a signal is delivered:**
  - Default action
  - Ignore signal
  - Call a user-defined function in the process
    → the ***signal handler***

- **Allows signals to be used like "user-space traps"**

Oldskool: `signal()`

- **Test your C parsing skills:**

```
#include <signal.h>

void (*signal(int sig, void (*handler)(int))) (int);
```

- **What does this mean?**

Oldskool: `signal()`

```
void (*signal(int sig, void (*handler)(int))) (int);
```

- **Unpacking this:**
  - A handler looks like
    `void my_handler(int);`
  - Signal takes two arguments…
    An integer (the signal type, e.g. ***`SIGPIPE`****)*
    A pointer to a handler function
  - … and returns a pointer to a handler function
    The previous handler,

- **"Special" `handler` arguments:**
  - **`SIG_IGN`** (ignore), **`SIG_DFL`** (default), **`SIG_ERR`** (error code)

Unix signal handlers

- **Signal handler can be called at *any time!***
- **Executes on the current user stack**
  - If process is in kernel, may need to retry current system call
  - Can also be set to run on a different (alternate) stack

⇒ **User process is in *undefined* state when signal delivered**

Implications

- **There is very little you can safely do in a signal handler!**
  - Can’t safely access program global or static variables
  - Some system calls are *re-entrant*, and can be called
    including signal() and sigaction()
    full list see in “man 7 signal”
  - Many C library calls cannot (including **`_r`** variants!)
  - Can sometimes execute a **`longjmp`** if you are careful

- **What happens if another signal arrives?**

Multiple signals

- If multiple signals of the *same* type are to be delivered, Unix will ***discard all but one.***

- If signals of *different* types are to be delivered, Unix will deliver them ***in any order.***

- Serious concurrency problem:
  How to make sense of this?

A better `signal()` POSIX `sigaction()`

```
#include <signal.h>

int sigaction(int signo,
              const struct sigaction *act,
              struct sigaction *oldact);

struct sigaction {
      void (*sa_handler)(int);
      sigset_t    sa_mask;
      int         sa_flags;
      void (*sa_sigaction)(int, siginfo_t *, void *);
};
```

New action for signal **signo**

Previous action is returned

Signal handler

Signals to be blocked in this handler (cf., **fd_set**)

More sophisticated signal handler (depending on flags)

Signals as upcalls

- **Particularly specialized (and complex) form of an *upcall***
  - Kernel RPC to user process
- **Other OSes use upcalls much more heavily**
  - Including Barrelfish
  - "Scheduler Activations": dispatch every process using an upcall instead of return
- ***Very* important structuring concept for systems!**