- Problem:
  - Imagine we want to communicate an n-byte buffer x from process $\mathbf{P}_i$ to process $\mathbf{P}_j$.
  - As described so far, the processes
    - are *totally* protected wrt. each other,
    - can be executed in *any* order,
    - can be suspended at *any* time,
    - can be remain suspended for *any* period, and
    - can be resumed at *any* time.
- Solution: we need mechanisms to
  1. identify the end-points,
  2. synchronise the end-points, and
  3. communicate the data,

  i.e., **Inter-Process Communication (IPC)**.

- Note that:
  - most UNIX-like kernels support *several* IPC interfaces,
  - some options are summarised by

Type	Standard	Mechanism	Identifier
Synchronisation	System V	semaphore	keyed
	POSIX	semaphore	named or unnamed
Notification	POSIX	signal	PID
Communication	System V	shared memory	keyed
	POSIX	shared memory	named
	Linux	shared mapping	named or unnamed
	System V	message queue	keyed
	POSIX	message queue	named
	POSIX	pipe	named or unnamed
	POSIX	domain socket	named or unnamed

  but we'll focus on a few only.

IPC-related synchronisation: semaphore (1)

Definition

A **critical region** (or **critical section**) is a portion of a (multi-threaded) program that may not be executed concurrently (i.e., not executed by more than one thread of execution at the same time). A typical example is access to some shared resource, which, if it *were* concurrent, would fail somehow.

IPC-related synchronisation: semaphore (1)

Definition (Dijkstra [18])

A **semaphore** s is a counter, equipped with two operations

$$
\begin{array}{lcl}
V(s,x) & := & [\ s \leftarrow s + x\ ] \\
P(s,x) & := & \textbf{forever do } [\ \textbf{if } s \geq x \textbf{ then } s \leftarrow s - x, \textbf{ break }\ ]
\end{array}
$$

to increment and decrement it by x (typically $x = 1$). The semaphore is used to control concurrent access to some resource: intuitively, s is the number of concurrent users allowed (resp. "units" of the resource available) and P waits until access is allowed.

Definition

A **mutex** can be described as a *binary* semaphore (cf. a counting semaphore, a generalisation from 2 to n values) that simply allows or disallows access.

- ARMv7-A provides two forms of support in hardware, namely
  1. atomic load and store [17, Section 1.2.1]:

$$\texttt{ldrex r1, [r0]} \quad \mapsto \quad \left\{ \begin{array}{l} \mathsf{GPR}[1] \leftarrow \mathsf{MEM}[\mathsf{GPR}[0]] \\ \text{update monitor(s) wrt. address } x = \mathsf{GPR}[0] \end{array} \right.$$

$$\texttt{strex r2, r1, [r0]} \quad \mapsto \quad \left\{ \begin{array}{l} \textbf{if } \textit{monitor(s) allow access to address } x = \mathsf{GPR}[0] \textbf{ then} \\ \quad | \; \mathsf{MEM}[\mathsf{GPR}[0]] \leftarrow \mathsf{GPR}[1] \\ \quad | \; \mathsf{GPR}[2] \leftarrow 0 \\ \textbf{else} \\ \quad | \; \mathsf{GPR}[2] \leftarrow 1 \\ \textbf{end} \end{array} \right.$$

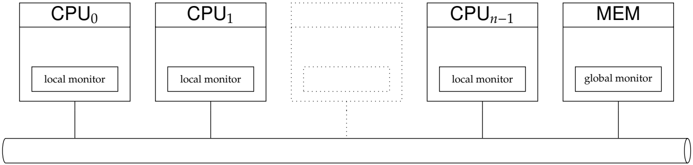
  2. atomic swap [17, Appendix A]:

$$\texttt{swp r2, r1, [r0]} \mapsto \left\{ \begin{array}{l} t \leftarrow \mathsf{MEM}[\mathsf{GPR}[0]] \\ \mathsf{MEM}[\mathsf{GPR}[0]] \leftarrow \mathsf{GPR}[2] \\ \mathsf{GPR}[1] \leftarrow t \end{array} \right.$$

  the former of which is now (strongly) preferred.

IPC-related synchronisation: semaphore (3)
ARMv7-A synchronisation primitives

- Idea: hardware-based **exclusive access monitors**.



  - two types, namely local and global, of monitor are operated; these are essentially state machines,
  - for a given access to MEM[x],

    1. non-shared region $\Rightarrow$ checked wrt. local *only*
    2. shared region $\Rightarrow$ checked wrt. local *plus* global monitor

  - `ldrex` from address x succeeds, but updates the monitor(s) by "tagging" (or remembering) x,
  - `strex` to address x succeeds iff. there was no more recent store wrt. x, otherwise need to retry.

IPC-related synchronisation: semaphore (6)

ARMv7-A synchronisation primitives

Listing ([17, Example 1-6])

```
sem_post: ldrex      r1, [ r0 ] ; s' = MEM[ &s ]
          add   r1, r1, #1      ; s' = s' + 1
          strex r2, r1, [ r0 ]  ; r <= MEM[ &s ] = s'
          cmp   r2, #0          ;    r  ?= 0
          bne   sem_post        ; if r  != 0, retry
          dmb                   ; memory barrier
          bx    lr              ; return
```

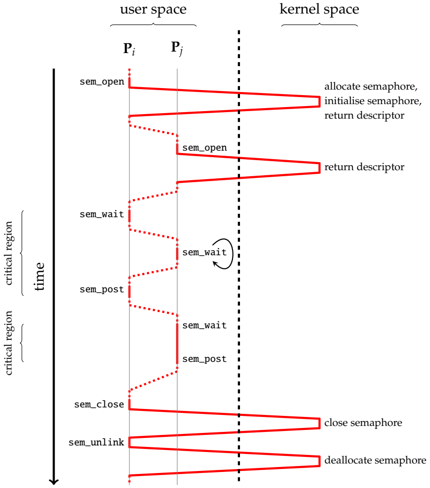
Listing ([17, Example 1-6])

```
sem_wait: ldrex      r1, [ r0 ] ; s' = MEM[ &s ]
          cmp   r1, #0          ;    s' ?= 0
          beq   sem_wait        ; if s' == 0, retry
          sub   r1, r1, #1      ; s' = s' - 1
          strex r2, r1, [ r0 ]  ; r <= MEM[ &s ] = s'
          cmp   r2, #0          ;    r  ?= 0
          bne   sem_wait        ; if r  != 0, retry
          dmb                   ; memory barrier
          bx    lr              ; return
```

- POSIX named semaphore API:
  - descriptor captured via type `sem_t`,
  - related operations performed via
    - `sem_open` [15, Page 1820]:
      - allocate semaphore if necessary

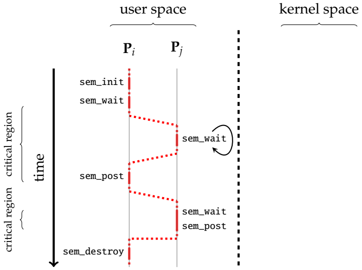
        $$\begin{array}{lcl} \texttt{flg} \ni \texttt{O\_CREAT} & \Rightarrow & \text{allocate} \\ \texttt{flg} \ni \texttt{O\_EXCL} & \Rightarrow & \text{allocate or fail} \end{array}$$

      - initialise semaphore value if necessary,
      - return descriptor.
    - `sem_wait` [15, Page 1832]:
      - decrement semaphore value,
      - block if necessary.
    - `sem_post` [15, Page 1823]:
      - increment semaphore value.
    - `sem_close` [15, Page 1812]:
      - close semaphore (i.e., stop using it).
    - `sem_unlink` [15, Page 1830]:
      - unlink semaphore (i.e., deallocate it).



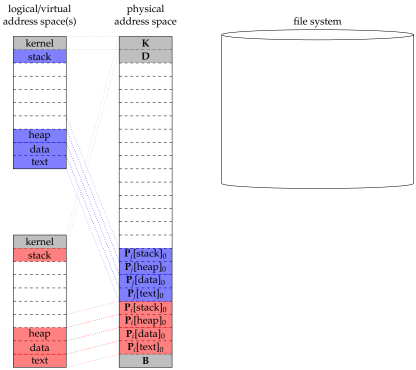
- POSIX unnamed semaphore API:
  - descriptor captured via type `sem_t`,
  - related operations performed via
    - `sem_init` [15, Page 1818]:
      - initialise semaphore value

        `shared` = 0 ⇒ shared between threads
        `shared` ≠ 0 ⇒ shared between processes
    - `sem_wait` [15, Page 1832]:
      - decrement semaphore value,
      - block if necessary.
    - `sem_post` [15, Page 1823]:
      - increment semaphore value.
    - `sem_destroy` [15, Page 1814]:
      - destroy semaphore (i.e., stop using it).



IPC-related communication: shared memory/mapping (1)

- **Idea**:

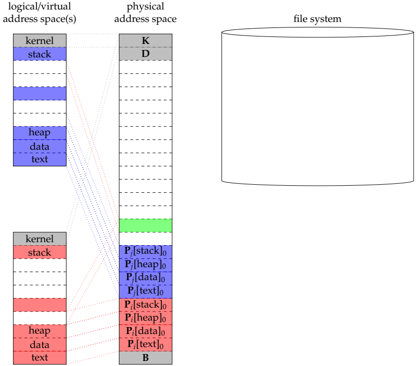


st.

– synchronisation needs to be explicit
± communication is unstructured (i.e., byte-oriented)
+ communication is (relatively) efficient
+ communication is bi-directional
+ supports *n*-to-*m* communication

IPC-related communication: shared memory/mapping (1)

- **Idea**:

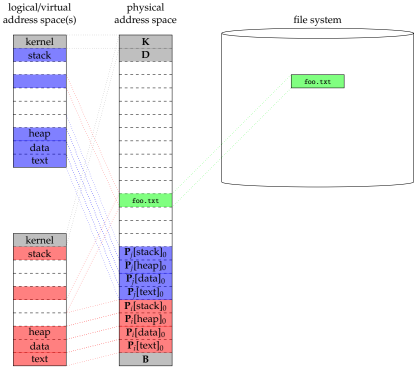


st.

- − synchronisation needs to be explicit
- ± communication is unstructured (i.e., byte-oriented)
- \+ communication is (relatively) efficient
- \+ communication is bi-directional
- \+ supports n-to-m communication

IPC-related communication: shared memory/mapping (1)

- Idea:



st.

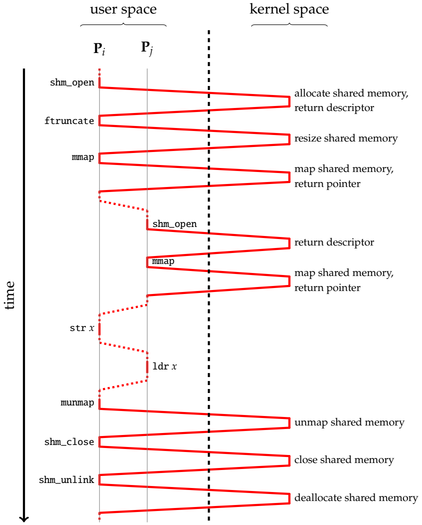
- – synchronisation needs to be explicit
- ± communication is unstructured (i.e., byte-oriented)
- + communication is (relatively) efficient
- + communication is bi-directional
- + supports *n*-to-*m* communication

IPC-related communication: shared memory/mapping (3)

- POSIX named shared memory API:
  - descriptor captured via type `int`,
  - related operations performed via
    - `shm_open` [15, Page 1898]:
      - allocate n-byte shared memory region if necessary

        $$\begin{array}{lcl} \texttt{flg} \ni \texttt{O\_CREAT} & \Rightarrow & \text{allocate} \\ \texttt{flg} \ni \texttt{O\_EXCL} & \Rightarrow & \text{allocate or fail} \\ \texttt{flg} \ni \texttt{O\_RDWR} & \Rightarrow & \text{read/write permission} \\ \texttt{flg} \ni \texttt{O\_RDONLY} & \Rightarrow & \text{read permission} \end{array}$$

      - return descriptor.
    - `mmap` [15, Page 1309]:
      - map shared memory region into virtual address space.
      - return pointer.
    - `munmap` [15, Page 1357]:
      - unmap shared memory region from virtual address space.
    - `shm_close`:
      - close shared memory region (i.e., stop using it).
    - `shm_unlink` [15, Page 1903]:
      - unlink shared memory region (i.e., deallocate it).



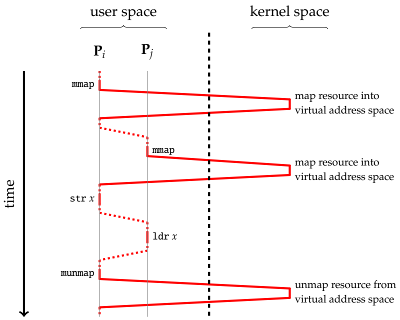
- Linux shared mapping API:
  - `mmap` [15, Page 1309]:
    - map resource into virtual address space

      `flg` ∋ `MAP_SHARED` ⇒ shared mapping
      `flg` ∋ `MAP_PRIVATE` ⇒ unshared mapping
      `flg` ∋ `MAP_ANONYMOUS` ⇒ memory mapping

    - initialise access permissions

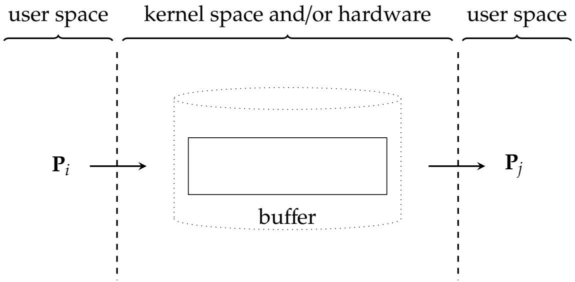
      `prot` ∋ `PROT_EXEC` ⇒ execute permission
      `prot` ∋ `PROT_READ` ⇒ read permission
      `prot` ∋ `PROT_WRITE` ⇒ write permission

    - return pointer.
  - `munmap` [15, Page 1357]:
    - unmap resource from virtual address space.



IPC-related communication: pipe (1)

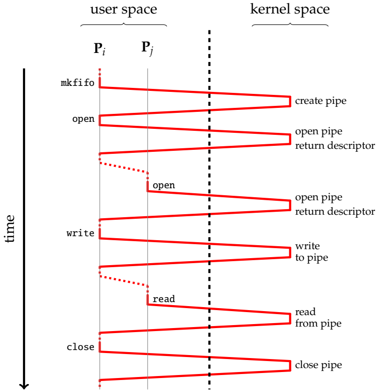
- Idea:



st.

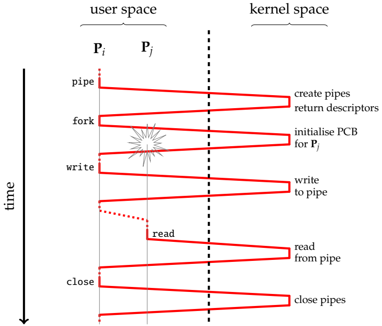
+ synchronisation is implicit
± communication is unstructured (i.e., byte-oriented)
− communication is (relatively) inefficient (i.e., vs. shared memory)
− communication is uni-directional
− supports 1-to-1 communication

- POSIX named pipe API:
  - descriptor captured via type `int`,
  - related operations performed via
    - `mkfifo` [15, Page 1295]:
      - allocate pipe,
      - initialise access permissions.
    - `open` [15, Page 1379]:
      - open pipe,
      - return descriptor.
    - `write` [15, Page 2263]:
      - write data to pipe,
      - block if necessary.
    - `read` [15, Page 1737]:
      - read data from pipe,
      - block if necessary.
    - `close` [15, Page 676]:
      - close pipe (i.e., stop using it).
    - `unlink` [15, Page 2154]:
      - unlink pipe (i.e., deallocate it).



IPC-related communication: pipe (2)
POSIX

- POSIX unnamed pipe API:
  - descriptor captured via type `int`,
  - related operations performed via
    - `pipe` [15, Page 1400]:
      - allocate pipes,
      - return descriptors.
    - `write` [15, Page 2263]:
      - write data to pipe,
      - block if necessary.
    - `read` [15, Page 1737]:
      - read data from pipe,
      - block if necessary.
    - `close` [15, Page 676]:
      - close pipe (i.e., stop using it).



Conclusions

- Take away points:
  - IPC is important, representing a core service delivered by kernel ...
  - ... *good* IPC is tricky, wrt.

    1. interface
       - large design space,
       - (ideally) needs to be flexible, uniform, etc.
       - can unify other abstractions (e.g., files, sockets),
       - should promote correctness,
    2. implementation
       - large design space,
       - needs to be efficient: pure overhead wrt. concurrent computation,
       - can share other mechanisms (e.g., files, sockets),
       - should enforce correctness,

    meaning *multiple*, complementary variants are the norm.

Conclusions

- Take away points:

  - A study of existing standards highlights design philosophy, e.g.,

$$
\text{System V} \mapsto \left\{ \begin{array}{lcl} \texttt{Xget} & \Rightarrow & \text{allocate resource and descriptor} \\ \texttt{Xctl} & \Rightarrow & \text{configure resource, plus deallocate descriptor and resource} \\ \texttt{Xop} & \Rightarrow & \text{general-purpose operation} \end{array} \right.
$$

$$
\text{POSIX} \mapsto \left\{ \begin{array}{lcl} \texttt{X\_open} & \Rightarrow & \text{allocate resource and descriptor, plus configure resource} \\ \texttt{X\_op} & \Rightarrow & \text{special-purpose operation} \\ \texttt{X\_close} & \Rightarrow & \text{deallocate descriptor} \\ \texttt{X\_unlink} & \Rightarrow & \text{deallocate resource} \end{array} \right.
$$

Additional Reading

- A.B. Downey. *The Little Book of Semaphores*. URL: http://greenteapress.com/wp/semaphores.
- M. Kerrisk. "Chapter 47: System V semaphores". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 53: POSIX semaphores". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 20: Signals: fundamental concepts". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 21: Signals: signal handlers". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 49: Memory mappings". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 48: System V shared memory". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 54: POSIX shared memory". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 46: System V message queues". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 52: POSIX message queues". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 44: Pipes and FIFOs". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- M. Kerrisk. "Chapter 57: Sockets: UNIX domain". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010.
- R. Love. "Chapter 4: Advanced file I/O". In: *Linux System Programming*. 2nd ed. O'Reilly, 2013.
- R. Love. "Chapter 10: Signals". In: *Linux System Programming*. 2nd ed. O'Reilly, 2013.

References

[1] A.B. Downey. *The Little Book of Semaphores*. URL: http://greenteapress.com/wp/semaphores (see p. 20).

[2] M. Kerrisk. "Chapter 20: Signals: fundamental concepts". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[3] M. Kerrisk. "Chapter 21: Signals: signal handlers". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[4] M. Kerrisk. "Chapter 44: Pipes and FIFOs". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[5] M. Kerrisk. "Chapter 46: System V message queues". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[6] M. Kerrisk. "Chapter 47: System V semaphores". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[7] M. Kerrisk. "Chapter 48: System V shared memory". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[8] M. Kerrisk. "Chapter 49: Memory mappings". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[9] M. Kerrisk. "Chapter 52: POSIX message queues". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[10] M. Kerrisk. "Chapter 53: POSIX semaphores". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[11] M. Kerrisk. "Chapter 54: POSIX shared memory". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[12] M. Kerrisk. "Chapter 57: Sockets: UNIX domain". In: *The Linux Programming Interface*. 6th ed. No Starch Press, 2010 (see p. 20).

[13] R. Love. "Chapter 10: Signals". In: *Linux System Programming*. 2nd ed. O'Reilly, 2013 (see p. 20).

[14] R. Love. "Chapter 4: Advanced file I/O". In: *Linux System Programming*. 2nd ed. O'Reilly, 2013 (see p. 20).

[15] *Standard for Information Technology - Portable Operating System Interface (POSIX)*. Institute of Electrical and Electronics Engineers (IEEE) 1003.1-2008. 2008. URL: http://standards.ieee.org (see pp. 8, 9, 13, 14, 16, 17).

References

[16] *ARM Architecture Reference Manual: ARMv7-A and ARMv7-R edition*. Tech. rep. DDI-0406C. ARM Ltd., 2014. URL: `http://infocenter.arm.com/help/topic/com.arm.doc.ddi0406c/index.html`.

[17] *ARM Synchronization Primitives*. Tech. rep. DHT-0008A. ARM Ltd., 2009. URL: `http://infocenter.arm.com/help/topic/com.arm.doc.dht0008a/index.html` (see pp. 5, 7).

[18] E.W. Dijkstra. *Over de sequentialiteit van procesbeschrijvingen*. Tech. rep. EWD-35. 1962 (approx.) URL: `http://www.cs.utexas.edu/users/EWD` (see pp. 3, 4).