The Process API (ch. 5)

Operating Systems
Based on: Three Easy Pieces by Arpaci-Dusseaux

Moshe Sulamy

Tel-Aviv Academic College

Process API

- API: Application Programming Interface
- The API of the OS: **system calls**
  - Function call into OS code
  - Higher privilege level, for sensitive operations (e.g., hardware)

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- The API of the OS: **system calls**
  - Function call into OS code
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- Rewrite code for each OS?
  - **POSIX API**: standard set for each POSIX-compliant OS (`write`)

POSIX hides OS specific details

fork xv6-x86

```
1  movl    $1, %eax
2  int     $64
```

fork Linux-x86

```
1  movl    $2, %eax
2  int     $128
```

close xv6-x86

```
1      pushl   fd
2      subl    $4,%esp
3      movl    $21,%eax
4      int     $64
5      addl    $4,%esp
```

close Linux-x86

```
1      movl    fd,%ebx
2      movl    $6,%eax
3      int     $128
```

Posix Process API

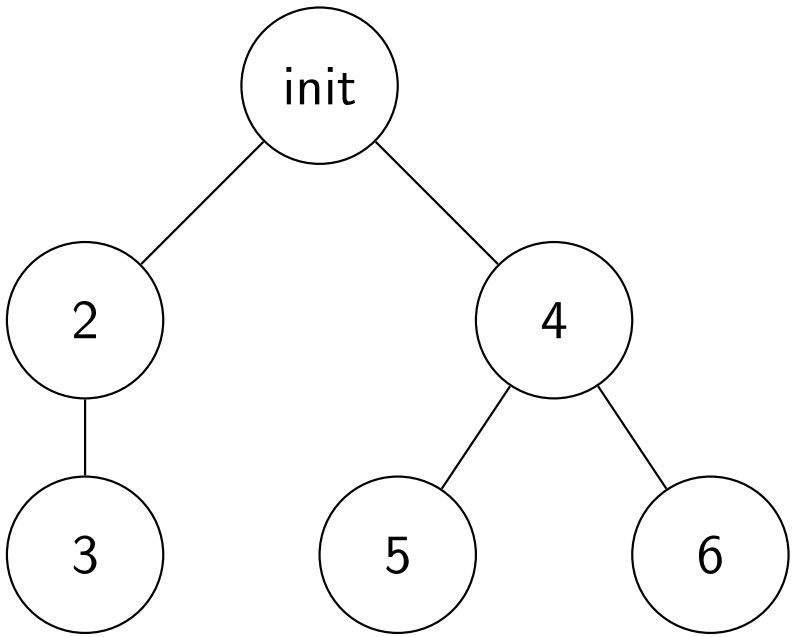
- `fork()`: create a new process
- `wait()`: block until a child process terminates
- `exec()`: make the process execute a given program

Process Tree

- Start with one process: `init` (PID 1)
- A process can create processes
  - Process A creates B: A is the **parent** of B, B is the **child** of A
  - Can create many children, only one parent
  - Parent can **wait** for child process to finish
- Process ID (**PID**): increasing identifier
  - Get PID: `getpid()`
  - Get parent PID: `getppid()`

Process Tree

- Processes form a tree:



- `ps --forest -eaf`
- `pstree`

`fork()`

- `fork()`: creates a new process
  - Wrapper for `clone` (in Linux)
- New process: almost exact copy of parent
  - Same: memory, execution point, open files
  - Different: PID, return value
  - **Copy-on-write** (Optimization)

`fork()`

- `fork()`: creates a new process
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- New process: almost exact copy of parent
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- Parent: `fork()` returns an integer:
  - If successful returns the **PID** of created child process
  - If fails negative number for erro code

`fork()`

- `fork()`: creates a new process
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- New process: almost exact copy of parent
  - Same: memory, execution point, open files
  - Different: PID, return value
  - **Copy-on-write** (Optimization)
- Parent: `fork()` returns an integer:
  - If successful returns the **PID** of created child process
  - If fails negative number for erro code
- Child process:
  - Begins to run at the point after the fork.
  - 'return value' is zero.

`fork` in details

```
1  pid = fork();
```

```
1      movl    $1,%eax
2      int     $64
3      movl    %eax,pid
```

Parent	Child
`1 movl $1,%eax` `2 int $64`	
`1 movl %eax,pid`	`1 movl %eax,pid`

fork()

Typical usage example (`fork.c`):

```
1  printf("hello world (pid:%d)\n", getpid());
2  int rc = fork();
3  if (rc < 0) {
4      fprintf(stderr, "fork failed\n");
5      exit(1);
6  }
7  else if (rc == 0) {
8      // child (new process)
9      // sleep(5);   // Try with and without
10     printf("I am child of %d (pid:%d)\n", getppid(), getpid());
11 }
12 else {
13     // parent
14     printf("I am parent of %d (pid:%d)\n", rc, getpid());
15 }
```

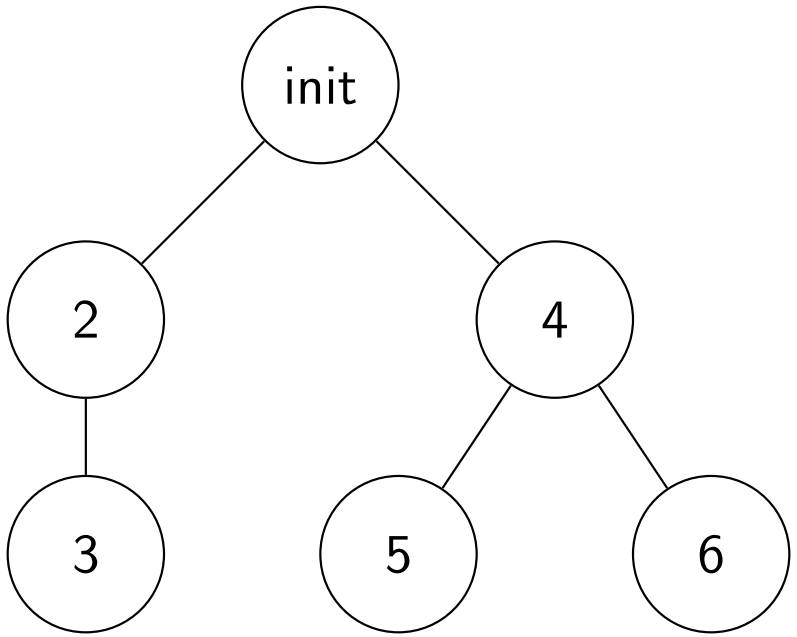
fork()

Output:

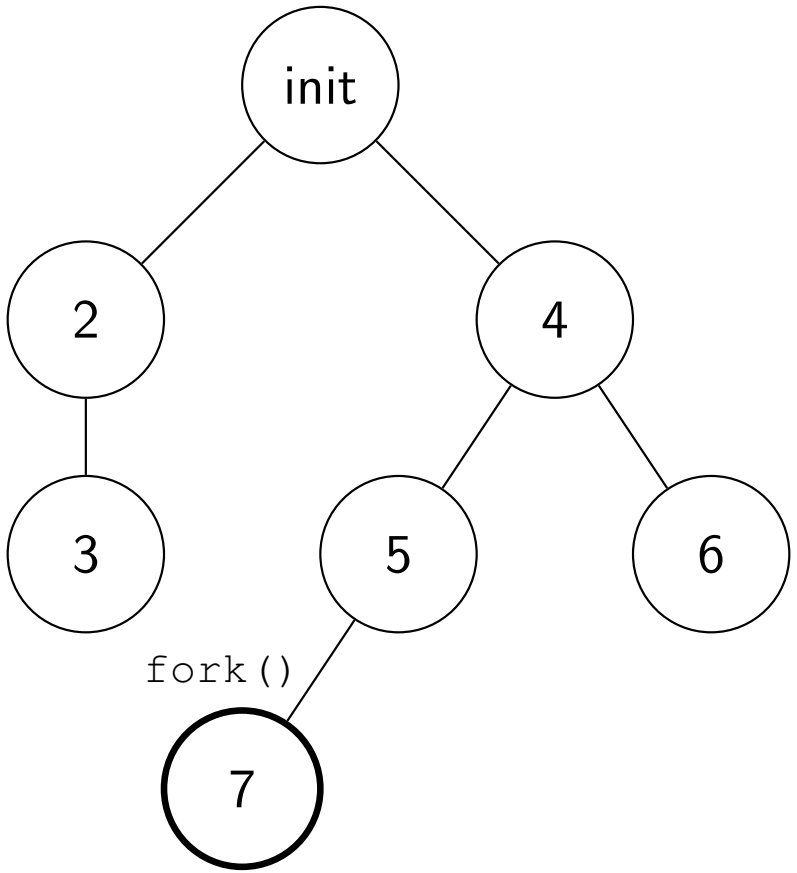
```
prompt> gcc -o fork fork.c -Wall
prompt> ./fork
hello world (pid:1300)
I am parent of 1301 (pid:1300)
I am child of 1 (pid:1301)
prompt>
```

- Child of **1**??

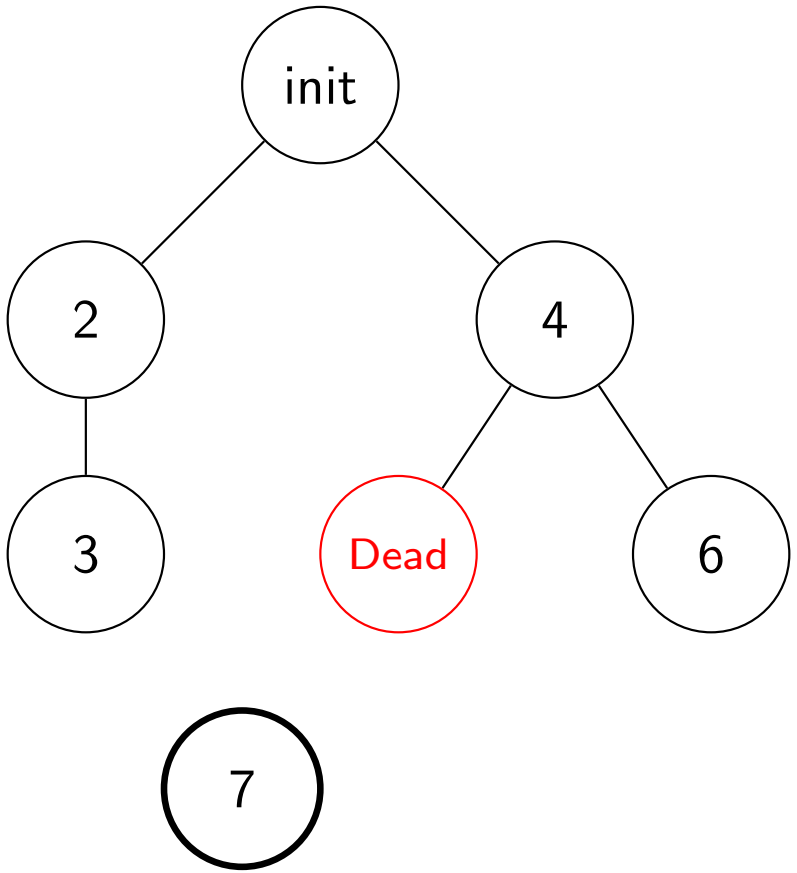
fork()



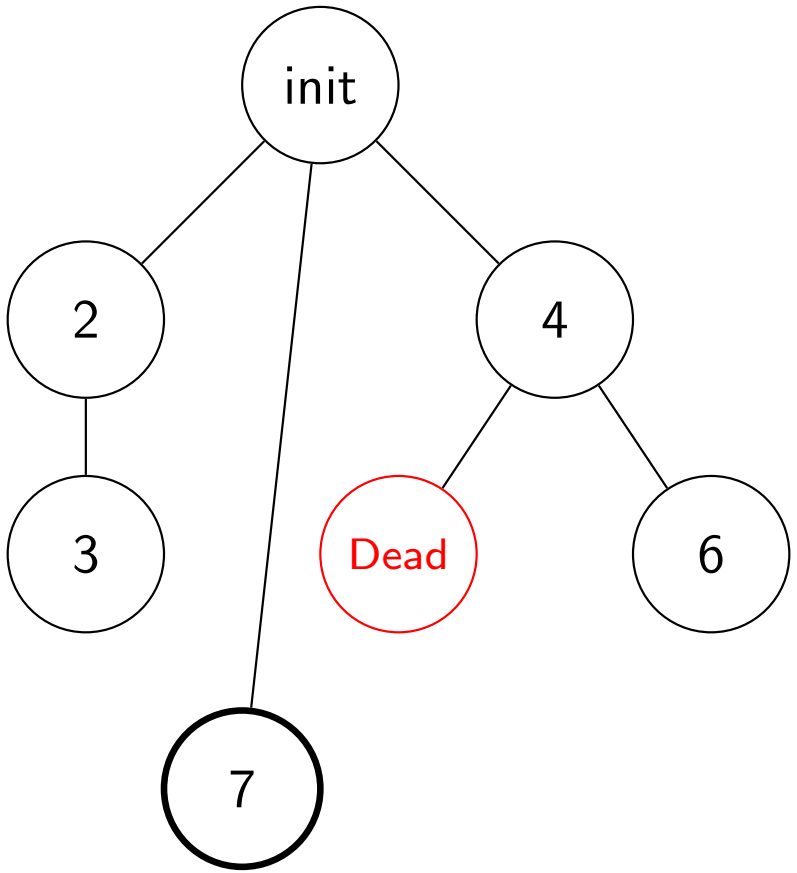
fork()



fork()



fork()



fork()

peculiar1.c:

```
1  int main(int argc, char *argv[])
2  {
3      fork();
4      fork();
5      printf("hello there\n");
6  }
```

What is the output?

fork()

peculiar1.c:

```
1 int main(int argc, char *argv[])
2 {
3     fork();
4     fork();
5     printf("hello there\n");
6 }
```

What is the output?

```
1 hello there
2 hello there
3 hello there
4 hello there
```

peculiar1

- P0 runs

peculiar1

- P0 runs
  - create P1 which begins on line 4

peculiar1

- P0 runs
  - create P1 which begins on line 4
  - create P2 which begins on line 5

peculiar1

- P0 runs
  - create P1 which begins on line 4
  - create P2 which begins on line 5
  - prints.

peculiar1

- P0 runs
  - create P1 which begins on line 4
  - create P2 which begins on line 5
  - prints.
- P1 runs

peculiar1

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  - prints.
- P1 runs
  - create P3 which begins on line 5

peculiar1

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peculiar1

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peculiar1

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  - prints.
- P1 runs
  - create P3 which begins on line 5
  - prints
- P2 runs
  - prints
- P3 runs
  - prints

fork()

peculiar2.c:

```
1  int main(int argc, char *argv[])
2  {
3      int pid = fork();
4      if (pid)
5          fork();
6      fork();
7      printf("hello there\n");
8  }
```

What is the output?

fork()

peculiar2.c:

```
1  int main(int argc, char *argv[])
2  {
3      int pid = fork();
4      if (pid)
5          fork();
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What is the output?

fork()

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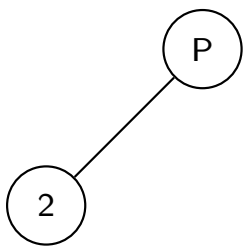

fork()

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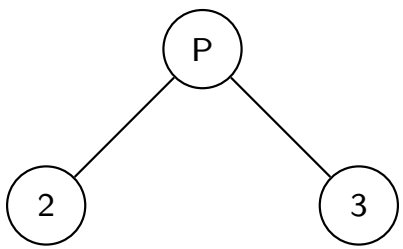

fork()

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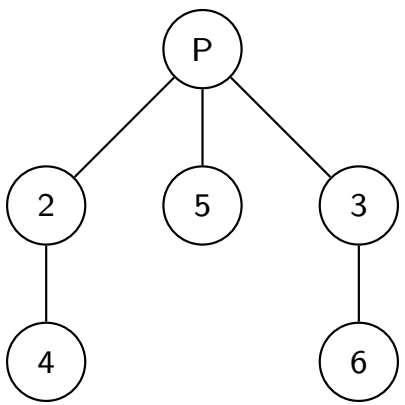

peculiar2

peculiar2

- P0 runs.

peculiar2

- P0 runs.
  - Creates P1 Line 4.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.
  - Create P5 line 7.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.
  - Create P5 line 7.
  - prints.

peculiar2

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- P1 runs.
  - Create P4 line 7.
  - prints.
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  - Create P5 line 7.
  - prints.
- P3 runs.

peculiar2

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  - prints.

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  - prints.
- P2 runs.
  - Create P5 line 7.
  - prints.
- P3 runs.
  - prints.
- P4 runs.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.
  - Create P5 line 7.
  - prints.
- P3 runs.
  - prints.
- P4 runs.
  - prints.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.
  - Create P5 line 7.
  - prints.
- P3 runs.
  - prints.
- P4 runs.
  - prints.
- P5 runs.

peculiar2

- P0 runs.
  - Creates P1 Line 4.
  - Creates P2 line 6.
  - Create P3 line 7
  - Prints.
- P1 runs.
  - Create P4 line 7.
  - prints.
- P2 runs.
  - Create P5 line 7.
  - prints.
- P3 runs.
  - prints.
- P4 runs.
  - prints.
- P5 runs.
  - prints.

fork()

peculiar3.c:

```
1 int main(int argc, char *argv[])
2 {
3     fork();
4     printf("hello\n");
5 }
```

Can this print "hehellollo"?

fork()

peculiar3.c:

```
1  int main(int argc, char *argv[])
2  {
3      fork();
4      printf("hello\n");
5  }
```

Can this print "hehellollo"?

- This is kernel implementaion dependent!
- Very important to consider these cases
- More on this in the future (**concurrency**)

fork()

peculiar4.c:

```
 1  int main(int argc, char *argv[])
 2  {
 3      int x = 0;
 4      if (fork()) {
 5          sleep(5); // BLOCKED state for 5 seconds
 6          printf("%d\n", x);
 7      }
 8      else {
 9          x += 3;
10      }
11  }
```

What is the output?

fork()

peculiar4.c:

```
 1  int main(int argc, char *argv[])
 2  {
 3      int x = 0;
 4      if (fork()) {
 5          sleep(5); // BLOCKED state for 5 seconds
 6          printf("%d\n", x);
 7      }
 8      else {
 9          x += 3;
10      }
11  }
```

What is the output? **0**

- Why?

fork()

peculiar4.c:

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 1  int main(int argc, char *argv[])
 2  {
 3      int x = 0;
 4      if (fork()) {
 5          sleep(5); // BLOCKED state for 5 seconds
 6          printf("%d\n", x);
 7      }
 8      else {
 9          x += 3;
10      }
11  }
```

What is the output? **0**

- Why? Child's memory is a **copy**

fork()

peculiar5.c:

```
1 fork();
2 if (fork()) {
3     fork();
4 }
5 fork();
```

How many processes does this code create?

fork()

peculiar5.c:

```
1  fork();
2  if (fork()) {
3      fork();
4  }
5  fork();
```

How many processes does this code create?

fork()

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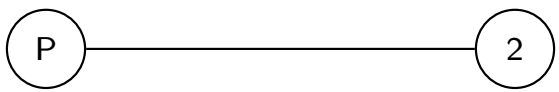

fork()

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```

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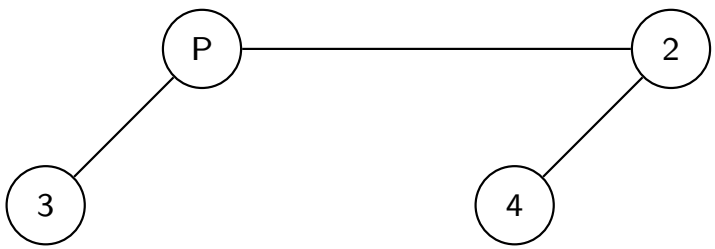

fork()

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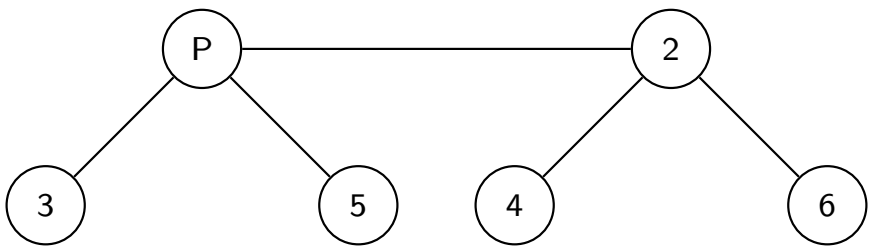

fork()

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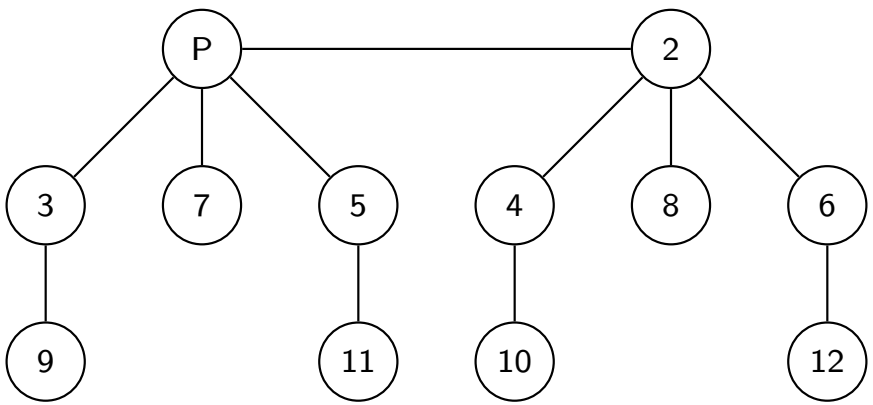


peculiar5

peculiar5

P0

peculiar5

P0

- P1 L2

peculiar5

P0

- P1 L2
- P2 L2.5

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

P1

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

P1

- P5 L2.5

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

P1

- P5 L2.5
- P6 L4

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

P1

- P5 L2.5
- P6 L4
- P7 L6

peculiar5

P0

- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

P1

- P5 L2.5
- P6 L4
- P7 L6

P2

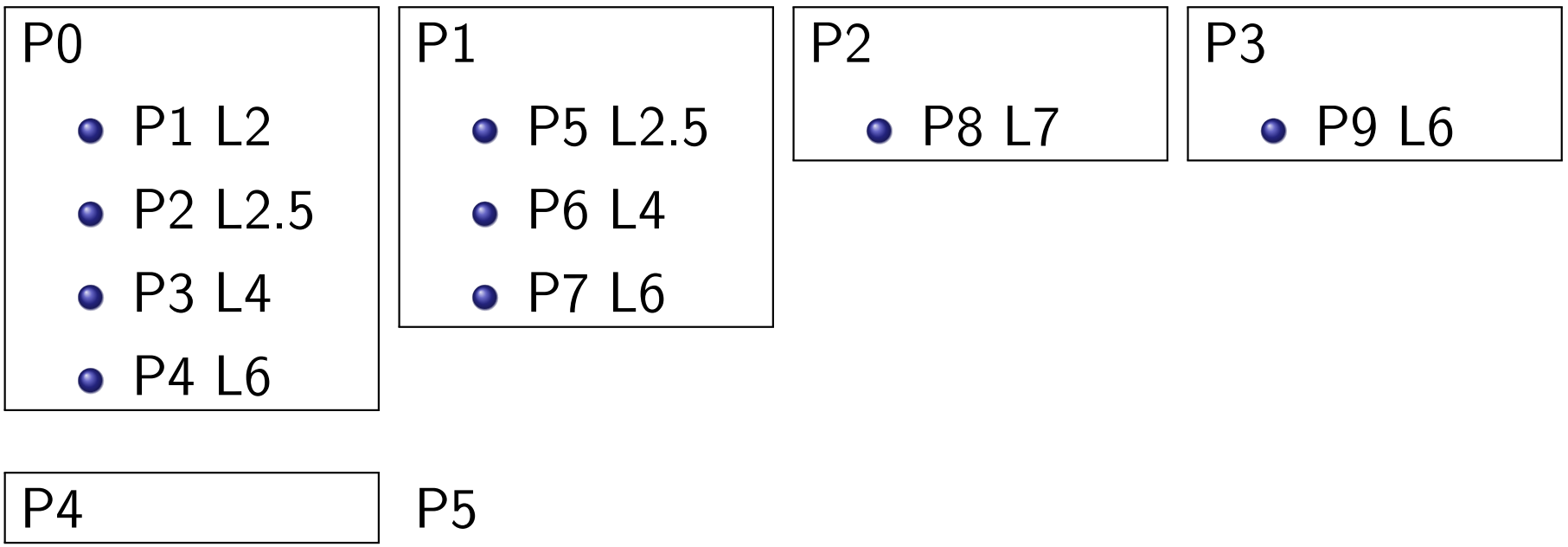
peculiar5

P0
- P1 L2
- P2 L2.5
- P3 L4
- P4 L6

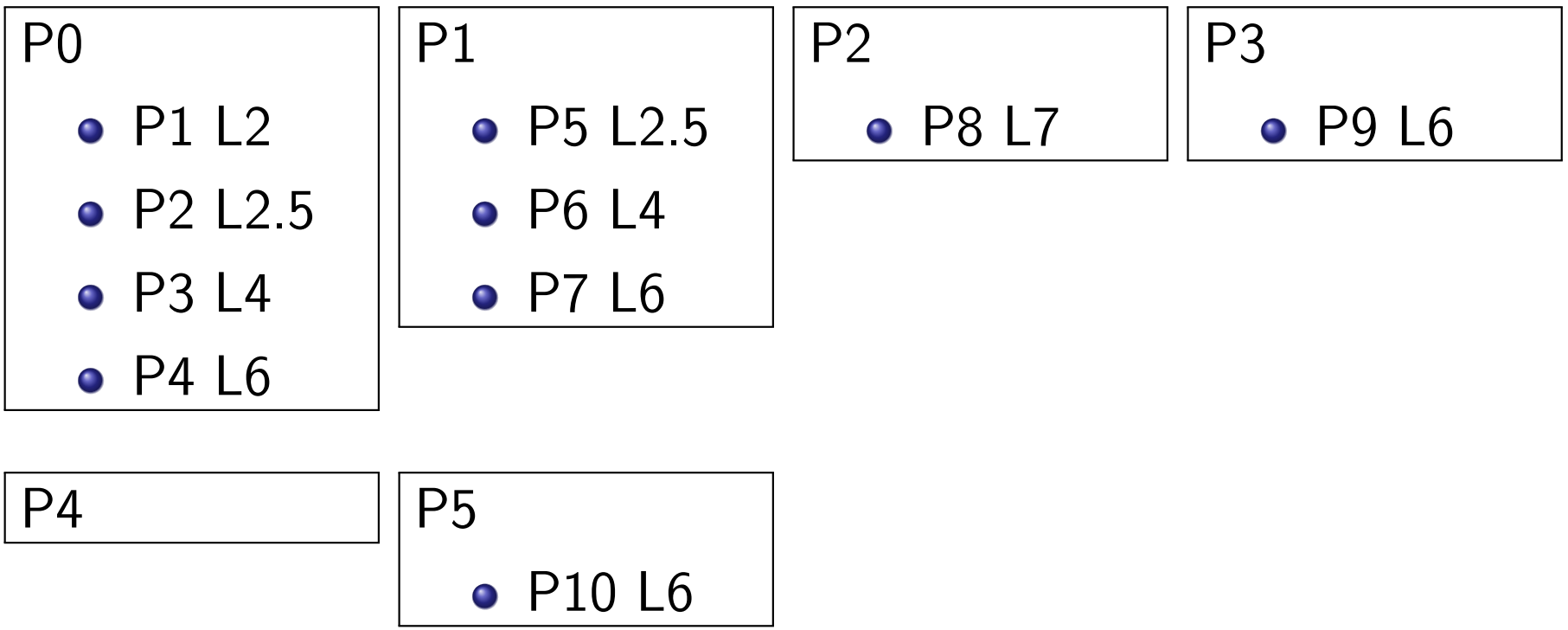
P1
- P5 L2.5
- P6 L4
- P7 L6

P2
- P8 L7

peculiar5


P0
P1 L2
P2 L2.5
P3 L4
P4 L6
P1
P5 L2.5
P6 L4
P7 L6
P2
P8 L7
P3
P9 L6
P4
P5

peculiar5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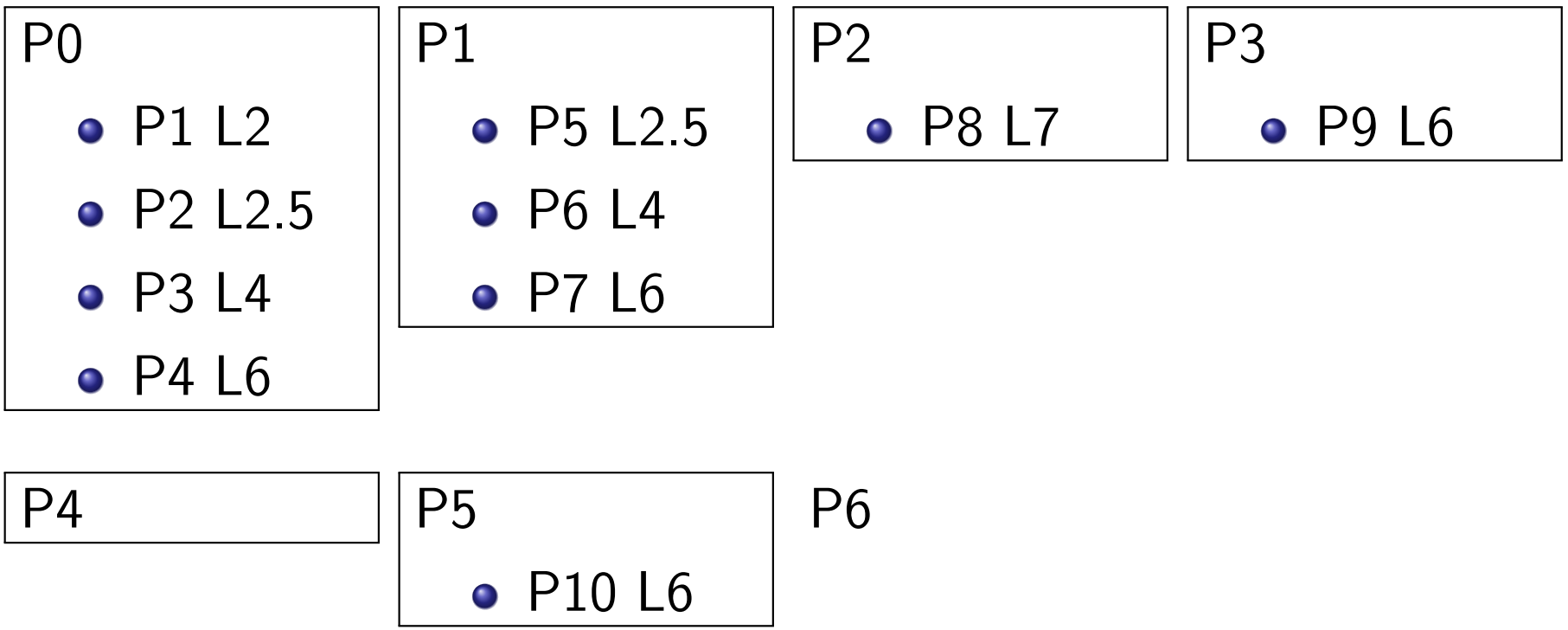
P2
P8 L7
P3
P9 L6
P4
P5
P10 L6

peculiar5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P3
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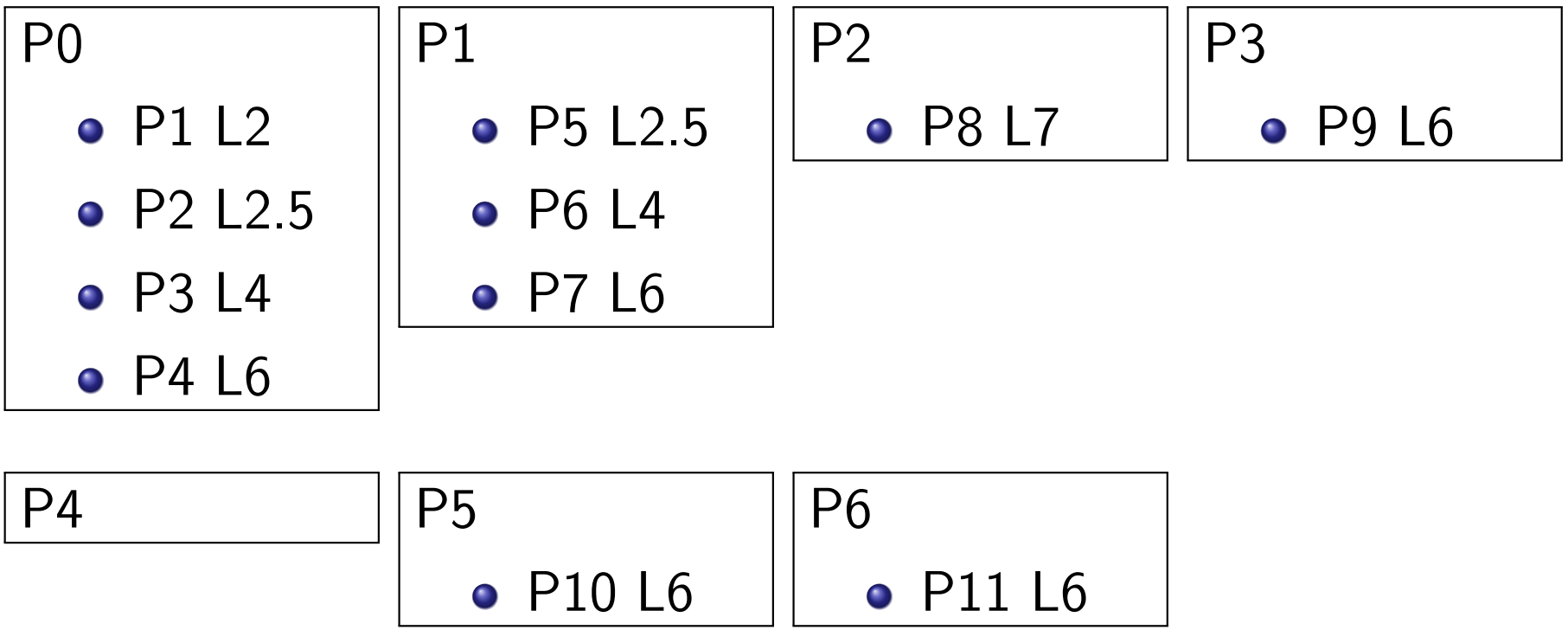
P4
P5
P10 L6
P6

peculiar5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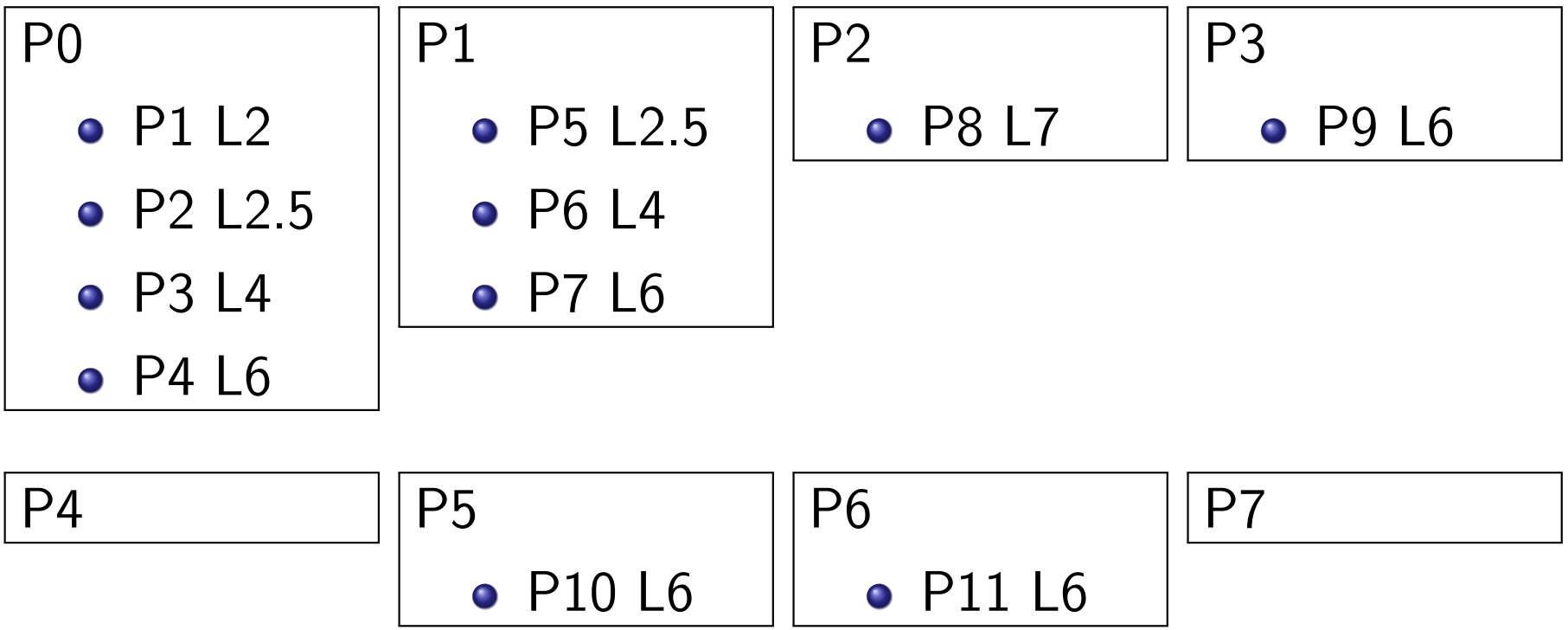
P4 L6
P1
P5 L2.5
P6 L4
P7 L6
P2
P8 L7
P3
P9 L6
P4
P5
P10 L6
P6
P11 L6

peculiar5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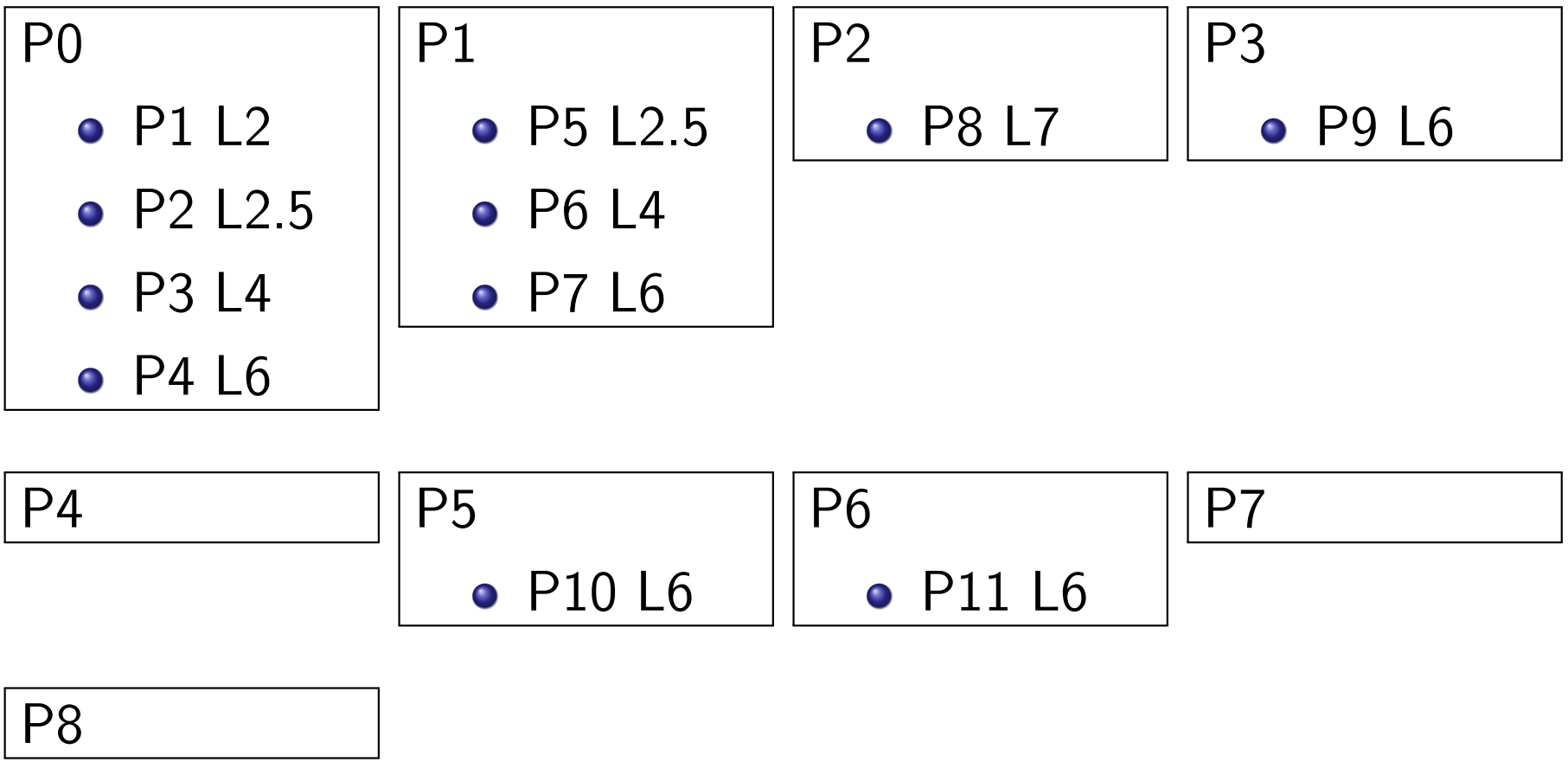
peculiar5


P0
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P9 L6
P4
P5
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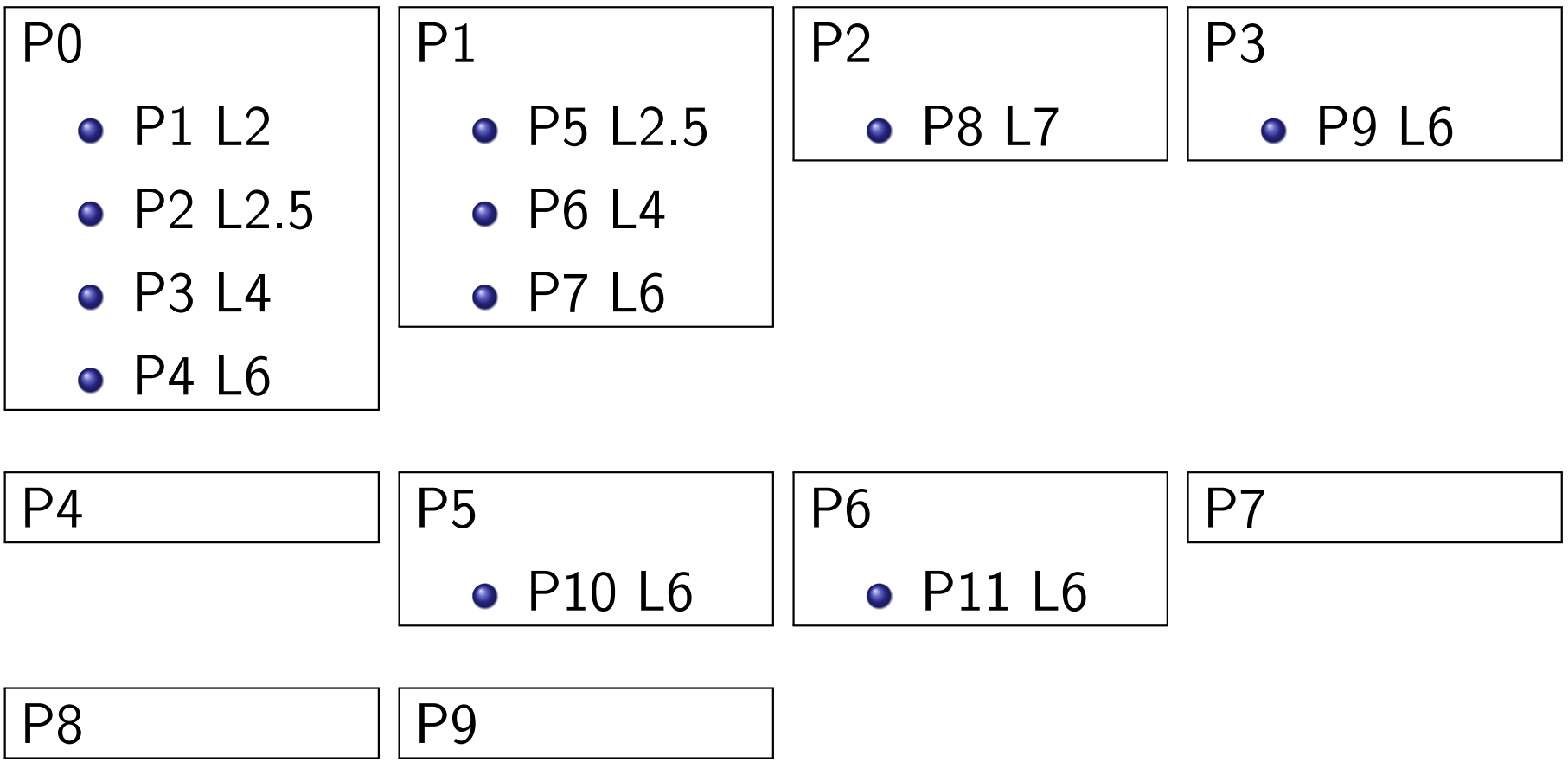
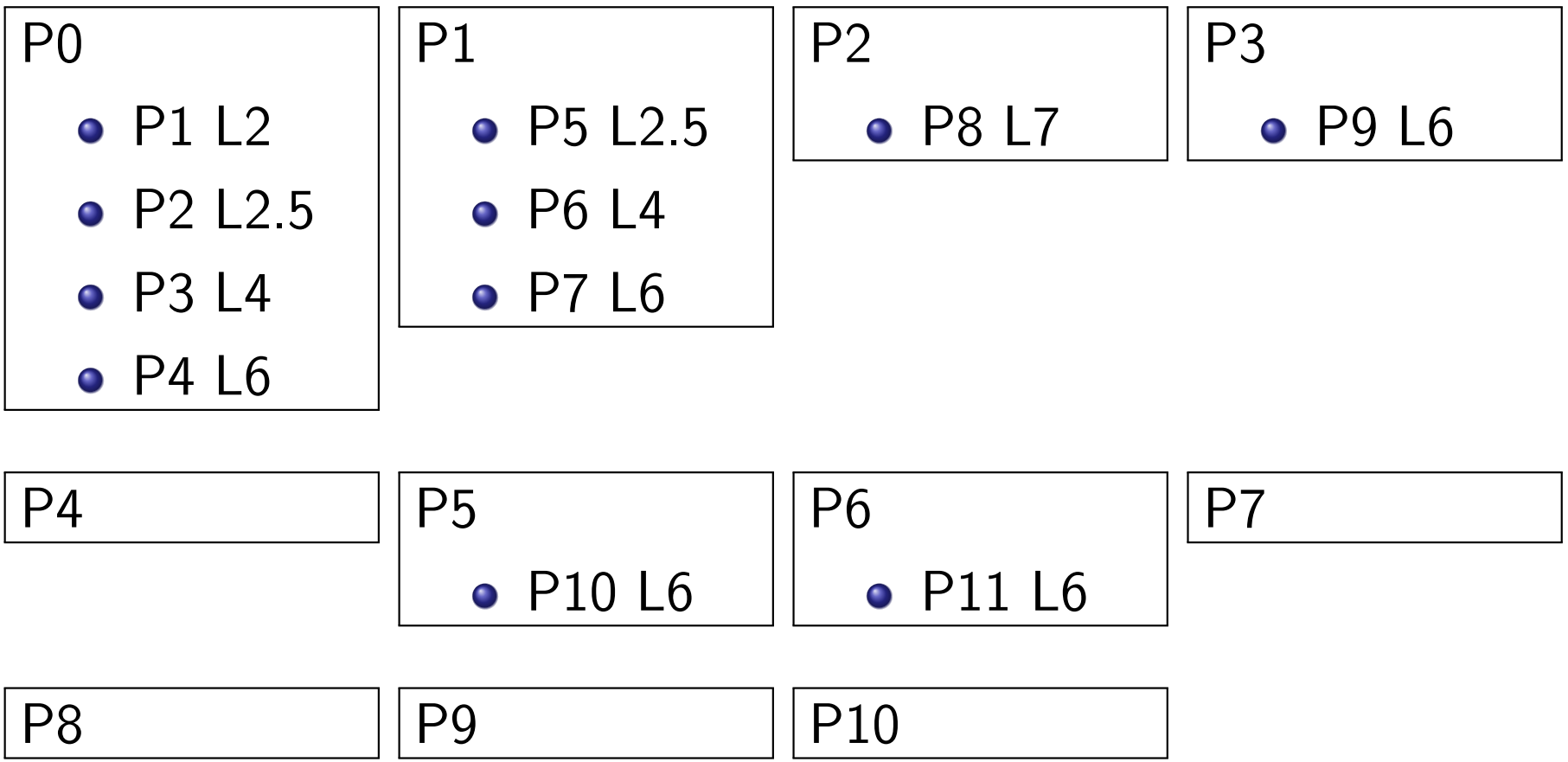
P6
P11 L6
P7
P8

peculiar5


P0
P1 L2
P2 L2.5
P3 L4
P4 L6
P1
P5 L2.5
P6 L4
P7 L6
P2
P8 L7
P3
P9 L6
P4
P5
P10 L6
P6
P11 L6
P7
P8
P9

peculiar5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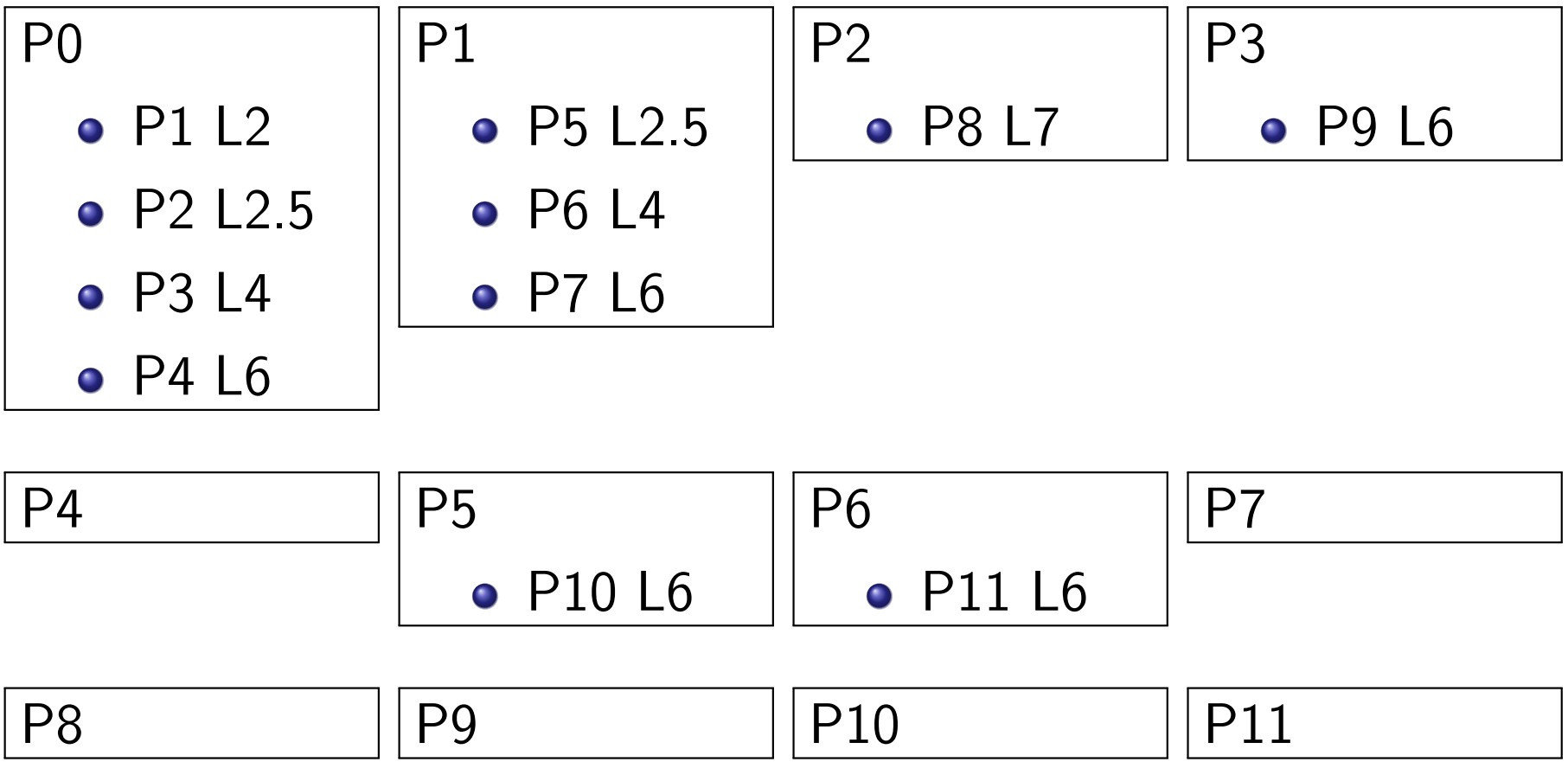
peculiar5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P11

fork()

peculiar6.c:

```
 1 int main(int argc, char *argv[])
 2 {
 3     int x = 0;
 4     if (fork()) {
 5         sleep(5); // Play with sleep
 6     }
 7     else {
 8         x += 3;
 9     }
10     printf(''%d'', x);
11 }
```

Last one - what is the output?

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Last one - what is the output? **30** or **03**

- Most chances 30
- Depends on scheduling
- Can we make it deterministic?

`wait()`

- `wait()`: waits for a child process to finish
  - Any child process (if several exist)
  - Returns PID of terminated child process (negative if no child)
  - `waitpid()`: waits for a specific child process (by PID)
- To wait for all child processes to end:
  - `while (wait(NULL) != -1);`

wait()

wait.c:

```
1  int main(int argc, char *argv[])
2  {
3      int x = 0;
4      int rc = fork();
5      if (rc) {
6          wait(NULL); // BLOCKED until child terminates
7          // equivalent here: waitpid(rc, NULL, 0);
8      }
9      else {
10         x += 3;
11     }
12     printf("%d", x);
13 }
```

Output is always **30**

exec()

- After `fork()`, parent and child execute same code
  - What if we want to run a different program?
  - `exec()` does just that
- Six variants of `exec()`: `execl`, `execlp`, `execle`, `execv`, `execvp`, `execvpe`. Read `man` for details

exec()

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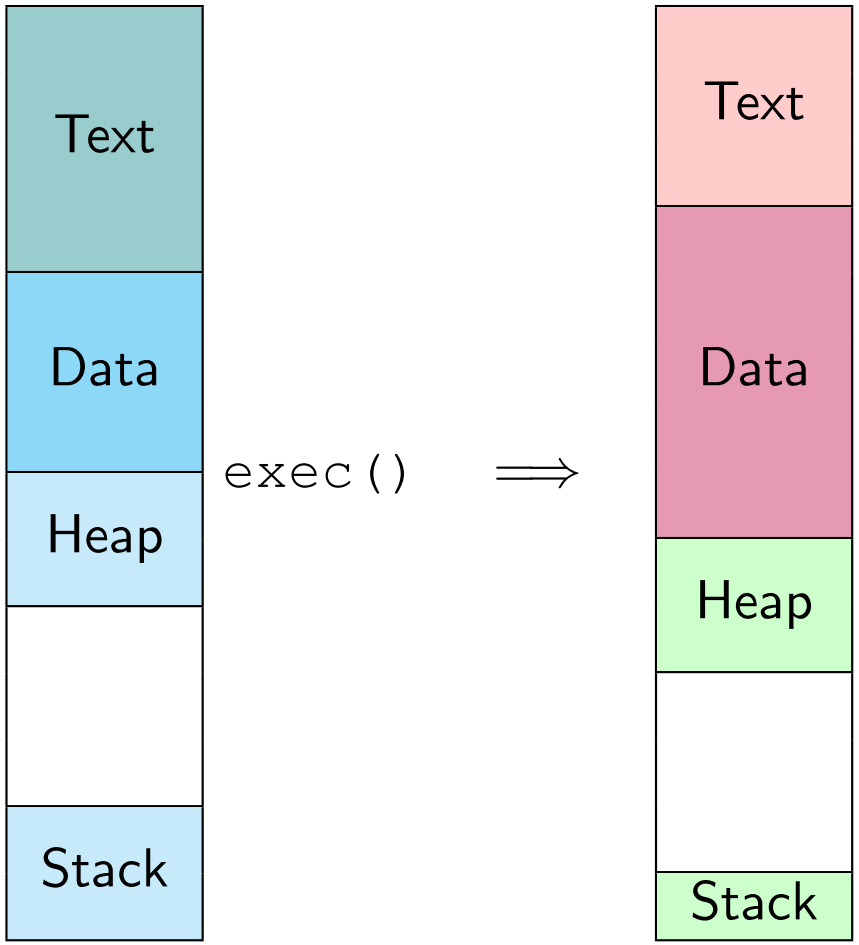
- `exec()`: Replaces current program with a different program
  - Receives program name and arguments (`argv`)
  - Overwrites and re-initializes process memory
  - A successful `exec()` never returns!

exec()



exec()

exec.c:

```
1  int main(int argc, char *argv[])
2  {
3      int rc = fork();
4      if (rc < 0) {
5          fprintf(stderr, "fork failed\n");
6          exit(1);
7      }
8      else if (rc == 0) {
9          char* args[4] = { "wc", "-l", "exec.c", NULL };
10         execvp(args[0], args);
11         printf("this shouldn't print out\n");
12     }
13     else {
14         int rc_wait = wait(NULL); // or waitpid(rc,NULL,0)
15         printf("I am parent of %d (rc_wait:%d) (pid:%d)\n",
16             rc, rc_wait, getpid());
17     }
18 }
```

The Living Dead

- When a process terminates, it remains in the process list as a **zombie**
  - Parent process may want to know its status
- Zombie remains until it is reaped (or its parent terminates)
  - Process 1 adpots orphans (zombied or live)

- A program should not leave zombies!

The Living Dead

- How to avoid zombies?
  - `wait()`: blocks until a child completes & reaps it
  - `waitpid()`: blocks until a specific child completes & reaps it
- Not enough
  - The terminal (shell) executes processes in the background, wants to continue accepting user input
  - It is possible to `wait()` without blocking, but very inconvenient
- What can we do?

Signals

- **Software interrupts**
  - Asynchronous notification of an event
  - Inter-process communication (**IPC**) or messages from OS

Signals

- **Software interrupts**
  - Asynchronous notification of an event
  - Inter-process communication (**IPC**) or messages from OS

- Various signals exist:
  - ^C in the terminal sends `SIGINT` ("interrupt from keyboard")
  - Invalid memory reference causes `SIGSEGV`
  - A process can send `SIGKILL` to another process
  - Child process terminated - **SIGCHLD**

Signal Handlers

- Some signals are handled automatically by the OS
  - `SIGKILL`, `SIGSTOP`
- Others are handled by a **signal handler**
  - Each signal has a default behavior, e.g., `SIGINT` causes the process to terminate
  - Can override default with `sigaction()`
- Let's write our own **signal handler**!

Signal Handlers

signal1.c:

```
 1  int main(int argc, char *argv[])
 2  {
 3      struct sigaction act;
 4      sigemptyset(&act.sa_mask);
 5      act.sa_handler = SIG_IGN;
 6      act.sa_flags = 0;
 7
 8      if (sigaction(SIGINT, &act, NULL) == -1) {
 9          fprintf(stderr, "sigaction failed\n");
10          exit(1);
11      }
12      while (1);
13  }
```

Signal Handlers

signal2.c:

```
1  void signal_handler(int signal) {
2      if (signal == SIGCHLD) {
3          int rc = wait(NULL);
4          printf("child terminated %d (pid:%d)\n", rc, getpid());
5      }
6  }
7  int main(int argc, char *argv[])
8  {
9      struct sigaction act;
10     sigemptyset (&act.sa_mask);
11     act.sa_handler = signal_handler;
12     act.sa_flags = 0;
13
14     sigaction(SIGCHLD, &act, NULL);
15     if (fork()) {
16         while (1);
17     }
18 }
```

No zombies!

`kill()`

- `kill()`: send a signal to another process
  - `kill(pid_t` *pid*`,` `int` *sig*`)`
  - *pid*: process id to send signal to
  - *sig*: signal to send
- Name is misleading
  - Can send any signal

Case Study

- How does a shell work?
  - Reads user command
  - Forks a child
  - Sets up process (e.g., redirection)
  - Execs the relevant program
  - Waits for it to finish (if not background)
  - Reads next command

Summary (Process API)

- `fork()`: create a new process (clone current)
- `wait()`: waits for a child process to finish
  - Also `waitpid()`
- `exec()`: transform program into a different program
  - Successful `exec()` never returns
- Terminated process remains as a **zombie**, to avoid:
  - Parent terminates
  - `wait()` or `waitpid()` by parent
- **Signals** are software interrupts
  - Can write our own **signal handlers**
  - Also helps with zombies
- `kill()`: send a signal to another process