Parallel computation

0. Parallelism that does not require programmer intervention

Pipelines

- CPU pipelines can be viewed as implementing some form of parallelism

  in the sense that multiple executions are being executed simultaneously

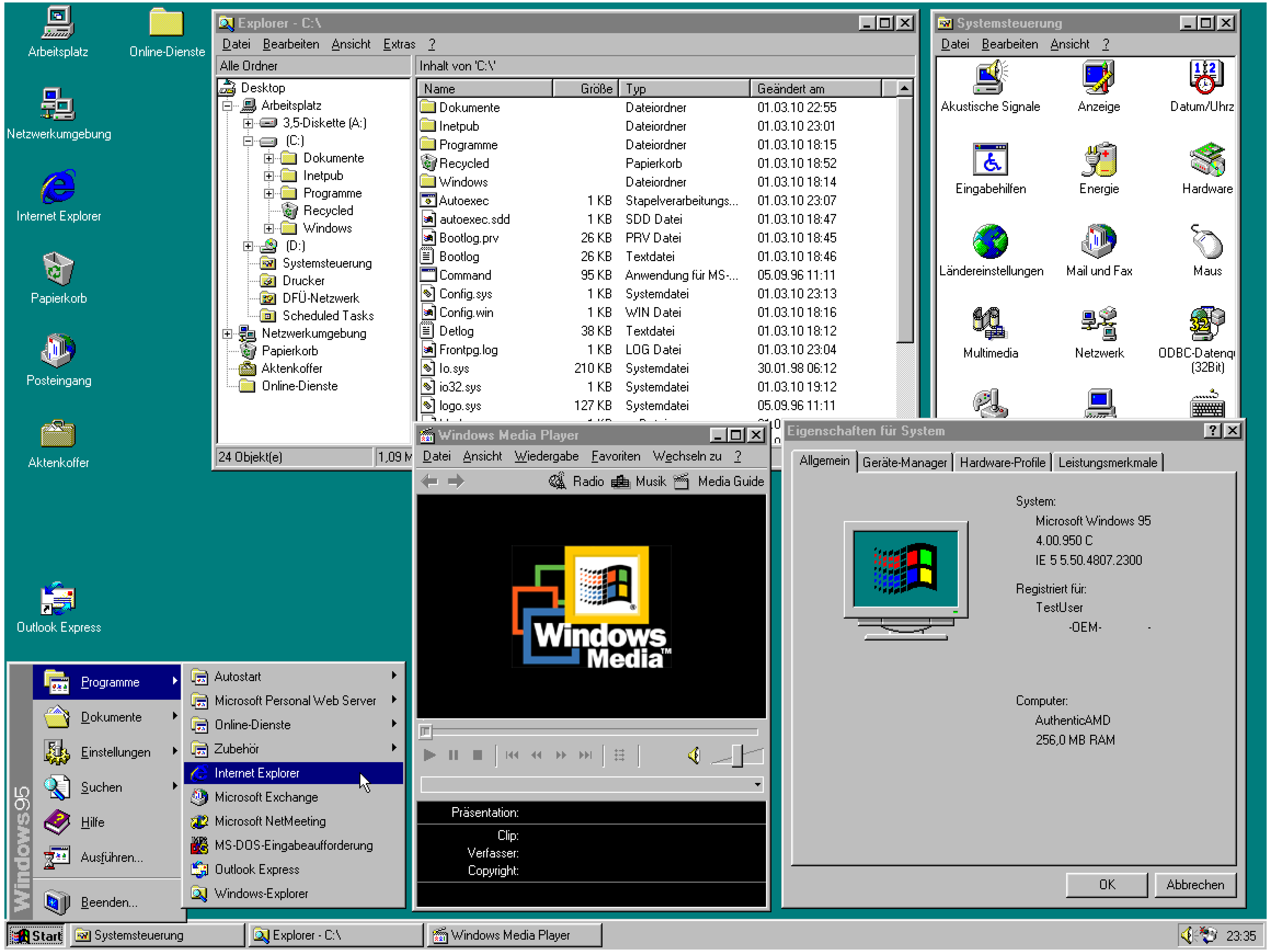
- For example, one instruction's arithmetic is performed (in an ALU)

  while the next is being decoded

- However, from the programmer's perspective,

  everything must happen **as if** there was no parallelism at all

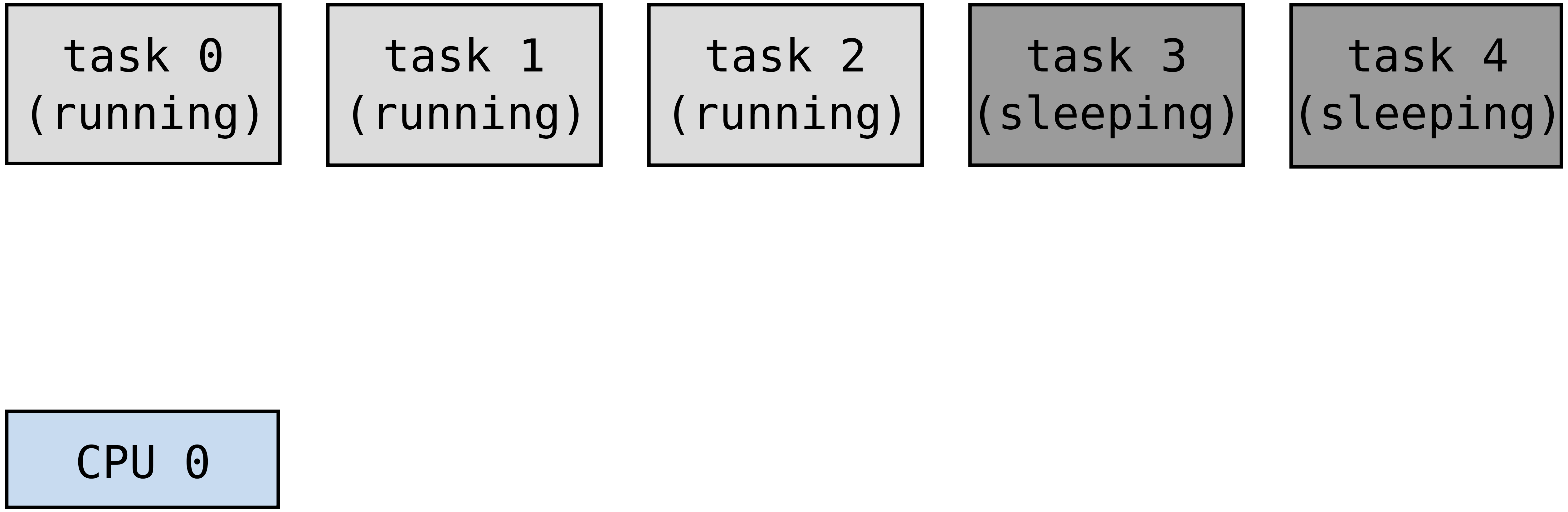
Multitasking



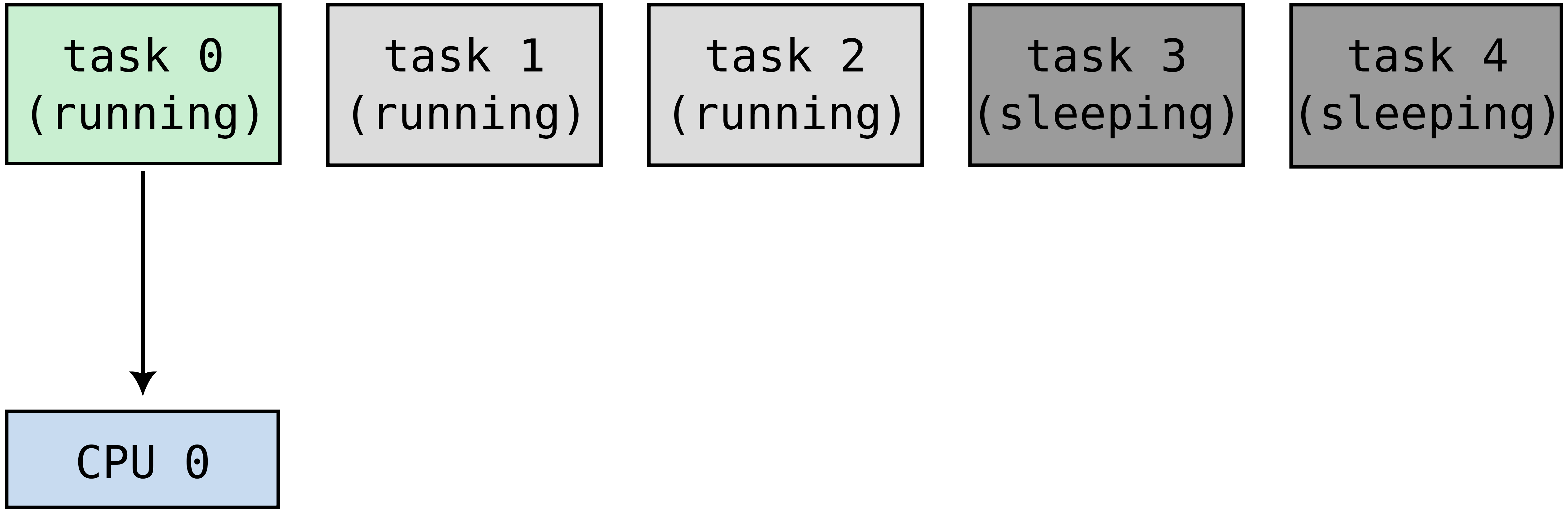
Multitasking

- Multitasking allows multiple executables to run “simultaneously” (even on a single processor)
- Regularly, the **scheduler** (part of the OS kernel) decides which **task** gets to run on a processor.

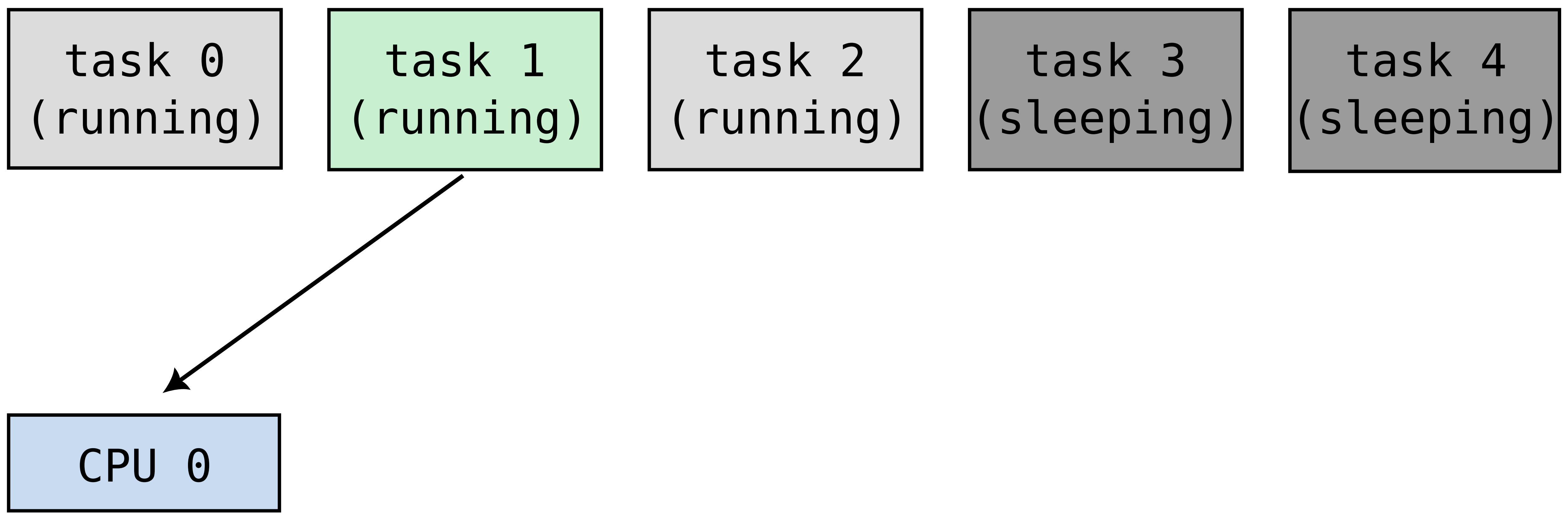
Multitasking on a single-core processor



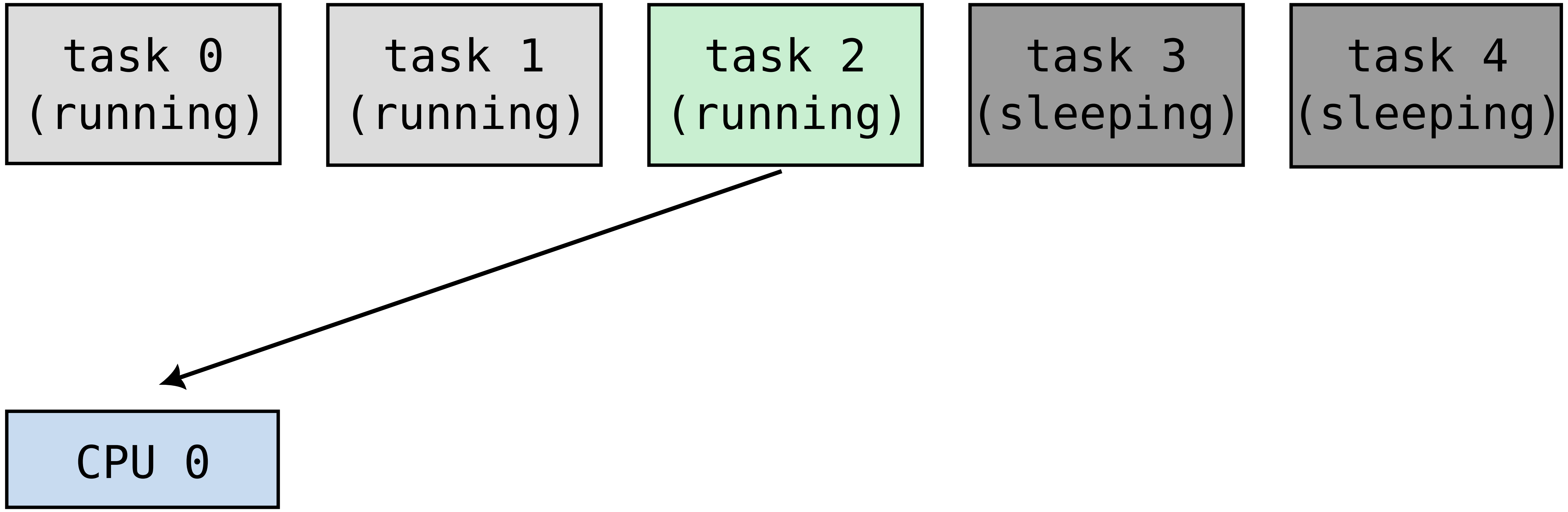
Multitasking on a single-core processor



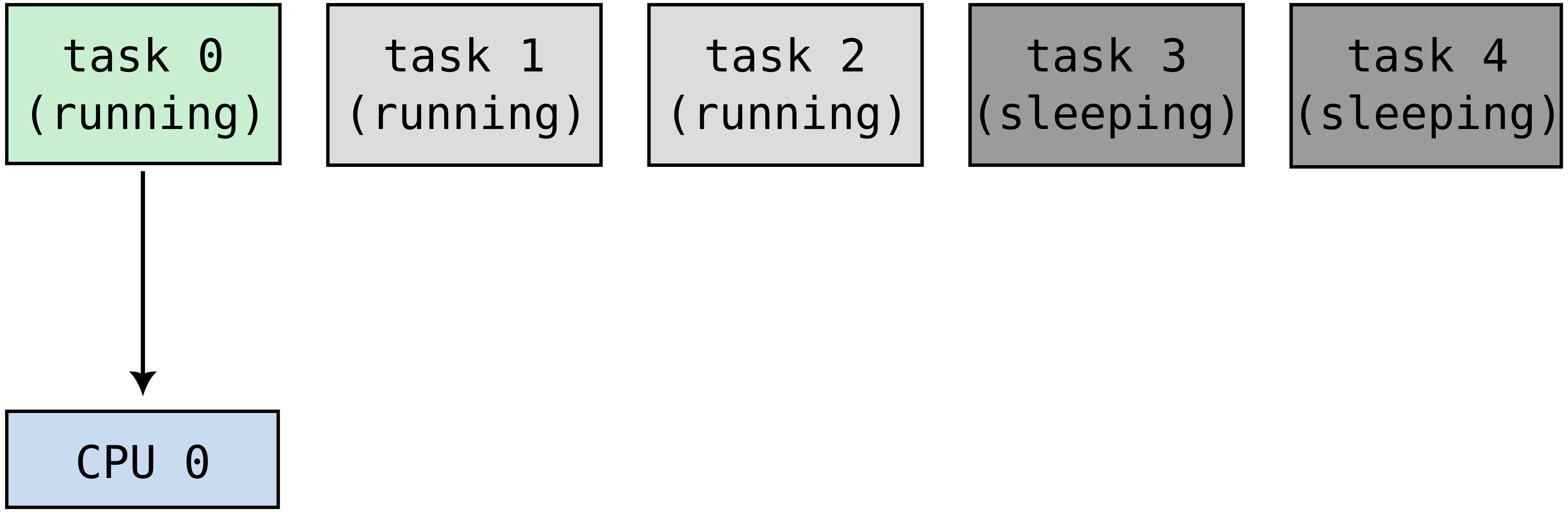
Multitasking on a single-core processor



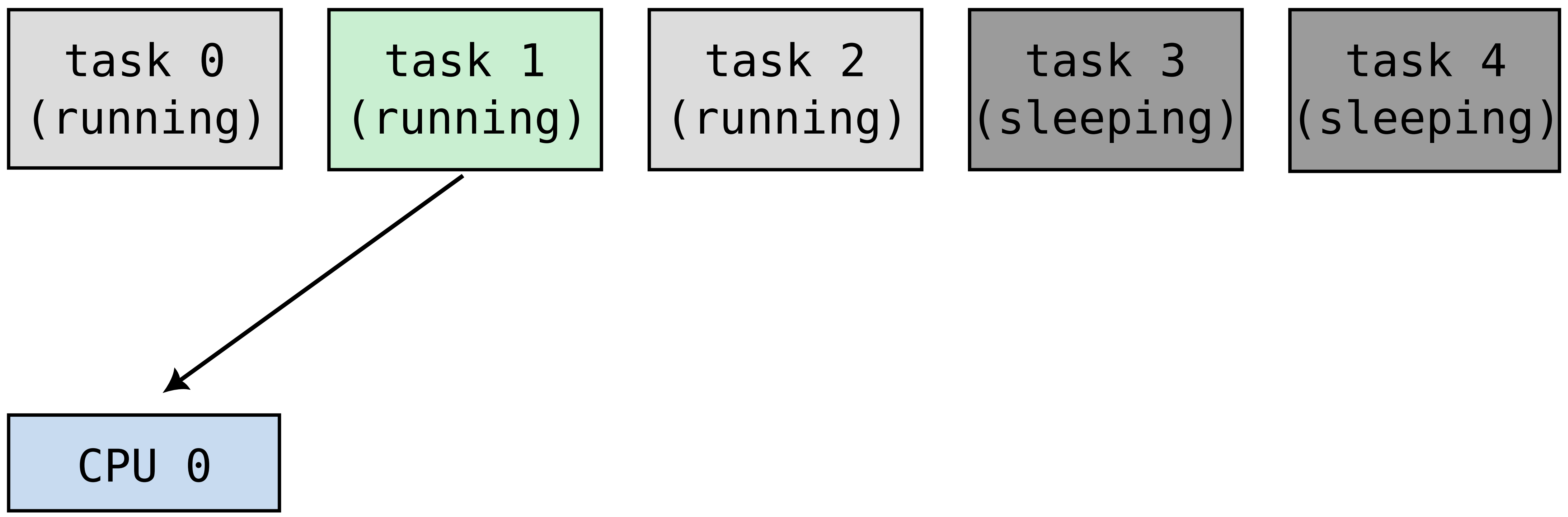
Multitasking on a single-core processor



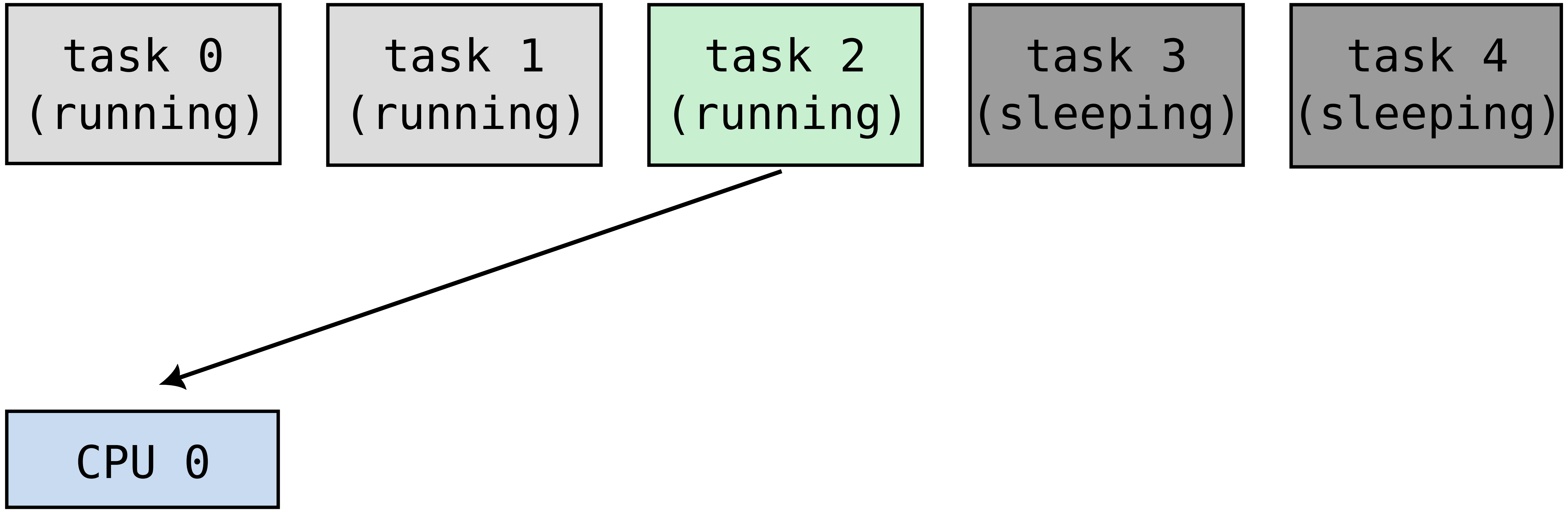
Multitasking on a single-core processor



Multitasking on a single-core processor



Multitasking on a single-core processor



- The scheduler is called:
  - at regular intervals f times per second, by default:
    - Linux: f = 1000 Hz (> see CONFIG_HZ)
    - MacOS: f = 100 Hz (> see sysctl kern.clockrate)
    - Windows 10: f = 64 Hz (> see timeBeginPeriod())
  - when an task performs a system call (`open()`, `write()`, `exit()`, ...)
  - when a "hardware interrupt" happens:
    - keyboard received a keypress
    - network device received data
    - storage device finished writing
    - sound/video device ready to receive next buffer
    - ...

Preemptive multitasking

- When the scheduler decides to interrupt a **running** process (e.g. to run another)
  - the process is said to "**preempted**"
  - it becomes "**runnable**"

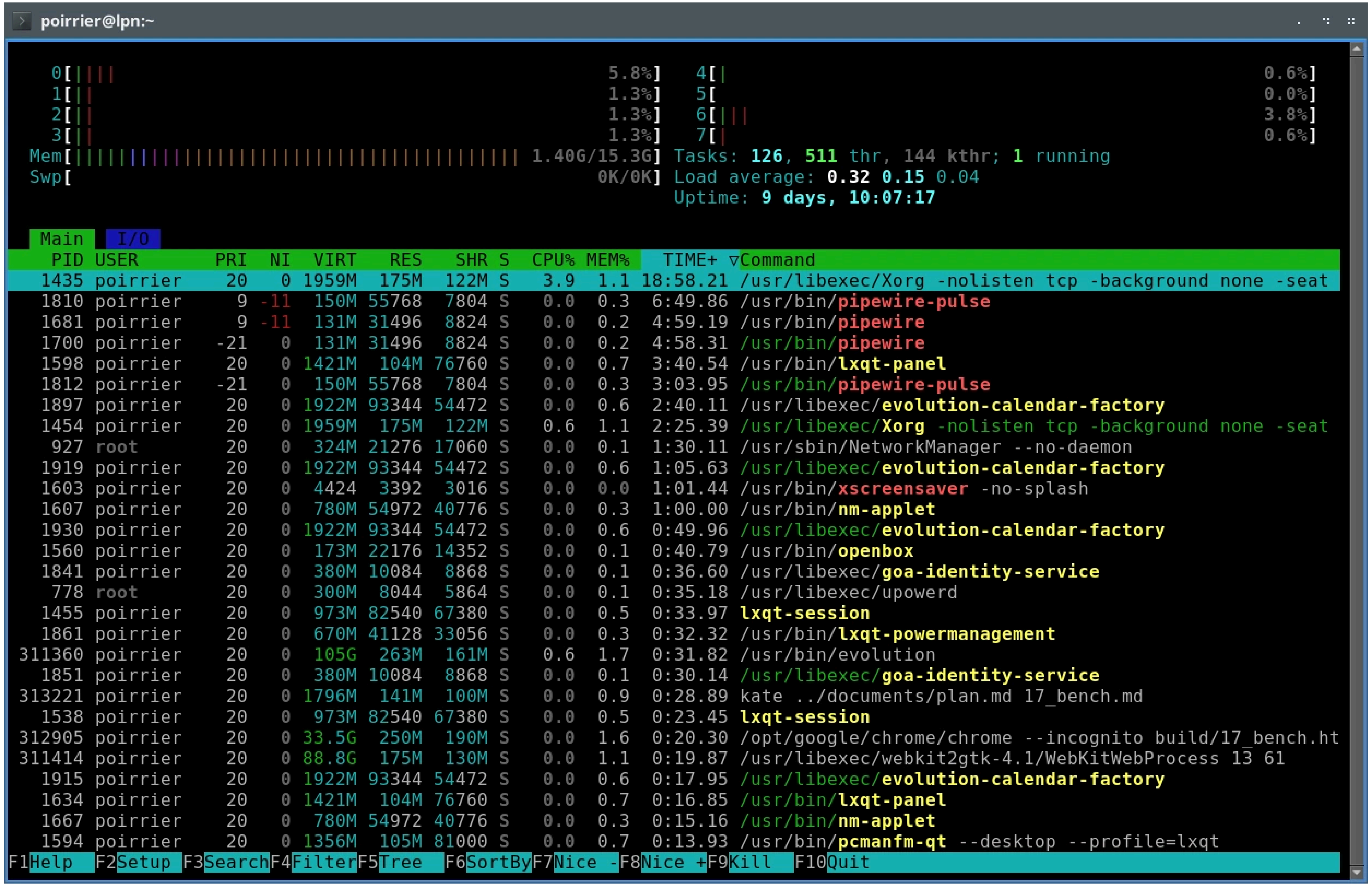
- When a process executes a system call,
  - it starts "**sleeping**"
  - after the requested operation is performed,
    - in some cases, it will **run** again
    - in other cases, it becomes **runnable** and will only run when a CPU is available
  - many system calls can take a long time to perform ("**blocking**" system calls):

    `read(), write(), recv(), send()`

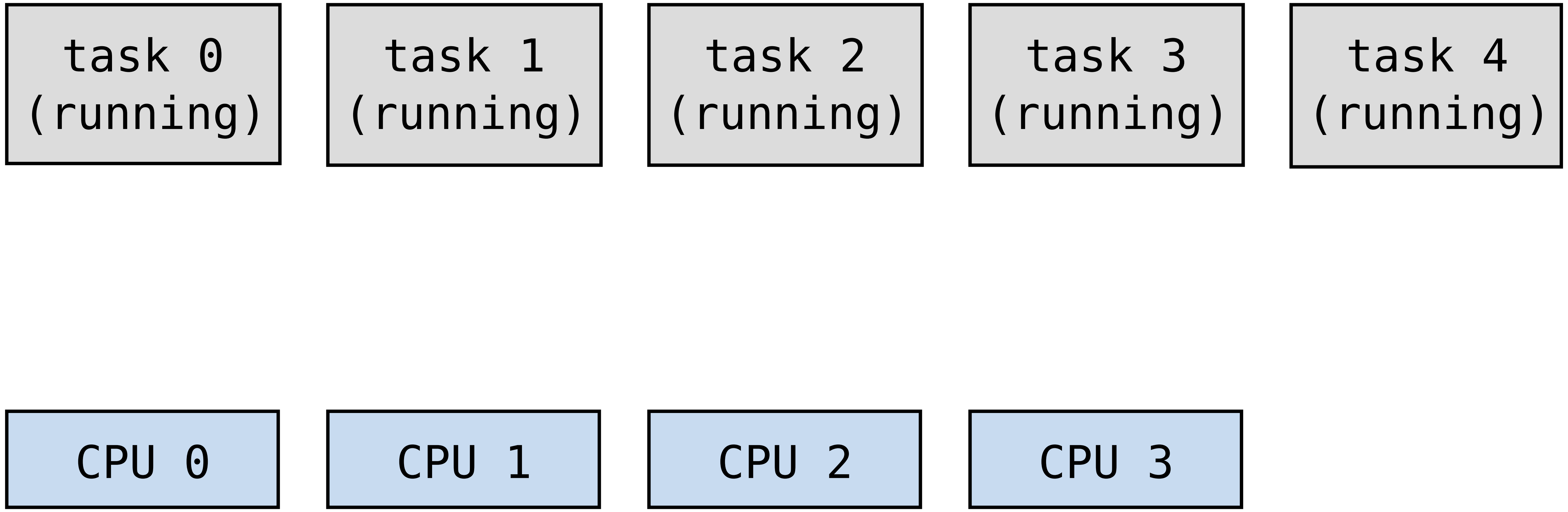
Preemptive multitasking

- At any given time, most tasks are **sleeping**
  - waiting for data (e.g. from network)
  - waiting for user interaction (e.g. keyboard or touch input)
  - waiting on a timer (tasks that run at regular interval)

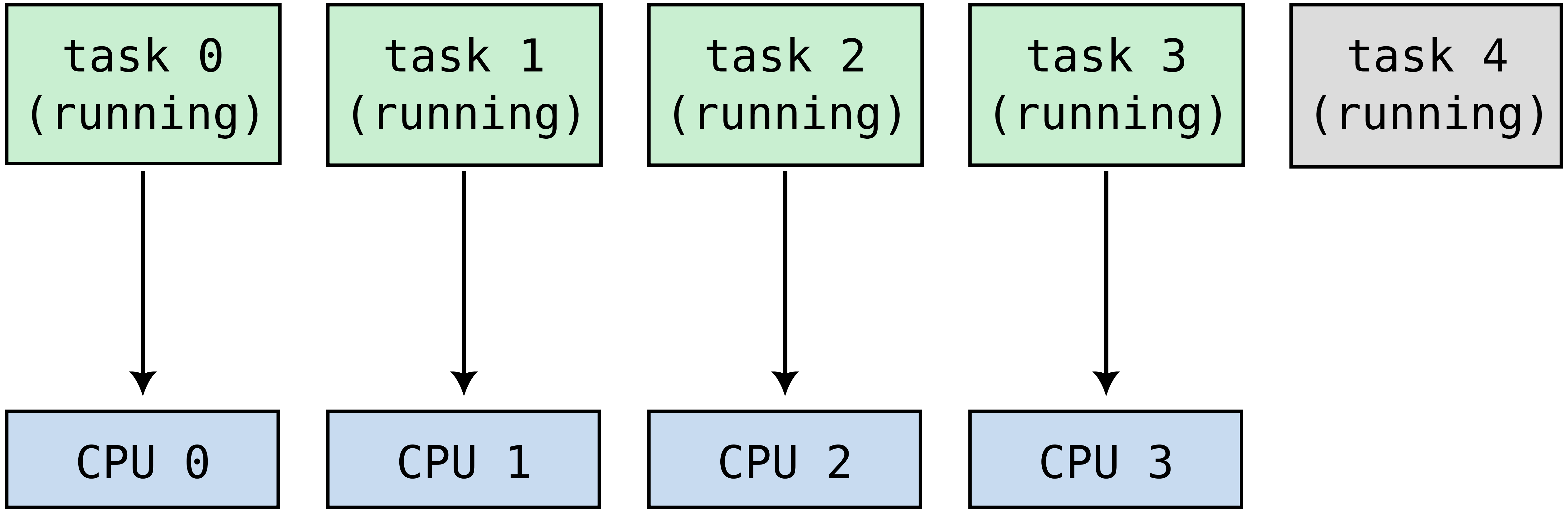
- The only tasks that are normally **running/runnable** are those performing CPU-intensive operations
  - graphics rendering
  - audio/video/data compression and decompression
  - computations
  - etc.


poirrier@lpn:~
0[|||| 5.8%]
1[|| 1.3%]
2[|| 1.3%]
3[|| 1.3%]
4[| 0.6%]
5[0.0%]
6[||| 3.8%]
7[| 0.6%]
Mem[||||||||||||||||||||||||||||||||||||||||| 1.40G/15.3G]
Swp[0K/0K]
Tasks: 126, 511 thr, 144 kthr; 1 running
Load average: 0.32 0.15 0.04
Uptime: 9 days, 10:07:17
Main
I/O
PID USER PRI NI VIRT RES SHR S CPU% MEM% TIME+ ▽Command
1435 poirrier 20 0 1959M 175M 122M S 3.9 1.1 18:58.21 /usr/libexec/Xorg -nolisten tcp -background none -seat
1810 poirrier 9 -11 150M 55768 7804 S 0.0 0.3 6:49.86 /usr/bin/pipewire-pulse
1681 poirrier 9 -11 131M 31496 8824 S 0.0 0.2 4:59.19 /usr/bin/pipewire
1700 poirrier -21 0 131M 31496 8824 S 0.0 0.2 4:58.31 /usr/bin/pipewire
1598 poirrier 20 0 1421M 104M 76760 S 0.0 0.7 3:40.54 /usr/bin/lxqt-panel
1812 poirrier -21 0 150M 55768 7804 S 0.0 0.3 3:03.95 /usr/bin/pipewire-pulse
1897 poirrier 20 0 1922M 93344 54472 S 0.0 0.6 2:40.11 /usr/libexec/evolution-calendar-factory
1454 poirrier 20 0 1959M 175M 122M S 0.6 1.1 2:25.39 /usr/libexec/Xorg -nolisten tcp -background none -seat
927 root 20 0 324M 21276 17060 S 0.0 0.1 1:30.11 /usr/sbin/NetworkManager --no-daemon
1919 poirrier 20 0 1922M 93344 54472 S 0.0 0.6 1:05.63 /usr/libexec/evolution-calendar-factory
1603 poirrier 20 0 4424 3392 3016 S 0.0 0.0 1:01.44 /usr/bin/xscreensaver -no-splash
1607 poirrier 20 0 780M 54972 40776 S 0.0 0.3 1:00.00 /usr/bin/nm-applet
1930 poirrier 20 0 1922M 93344 54472 S 0.0 0.6 0:49.96 /usr/libexec/evolution-calendar-factory
1560 poirrier 20 0 173M 22176 14352 S 0.0 0.1 0:40.79 /usr/bin/openbox
1841 poirrier 20 0 380M 10084 8868 S 0.0 0.1 0:36.60 /usr/libexec/goa-identity-service
778 root 20 0 300M 8044 5864 S 0.0 0.1 0:35.18 /usr/libexec/upowerd
1455 poirrier 20 0 973M 82540 67380 S 0.0 0.5 0:33.97 lxqt-session
1861 poirrier 20 0 670M 41128 33056 S 0.0 0.3 0:32.32 /usr/bin/lxqt-powermanagement
311360 poirrier 20 0 105G 263M 161M S 0.6 1.7 0:31.82 /usr/bin/evolution
1851 poirrier 20 0 380M 10084 8868 S 0.0 0.1 0:30.14 /usr/libexec/goa-identity-service
313221 poirrier 20 0 1796M 141M 100M S 0.0 0.9 0:28.89 kate ../documents/plan.md 17_bench.md
1538 poirrier 20 0 973M 82540 67380 S 0.0 0.5 0:23.45 lxqt-session
312905 poirrier 20 0 33.5G 250M 190M S 0.0 1.6 0:20.30 /opt/google/chrome/chrome --incognito build/17_bench.ht
311414 poirrier 20 0 88.8G 175M 130M S 0.0 1.1 0:19.87 /usr/libexec/webkit2gtk-4.1/WebKitWebProcess 13 61
1915 poirrier 20 0 1922M 93344 54472 S 0.0 0.6 0:17.95 /usr/libexec/evolution-calendar-factory
1634 poirrier 20 0 1421M 104M 76760 S 0.0 0.7 0:16.85 /usr/bin/lxqt-panel
1667 poirrier 20 0 780M 54972 40776 S 0.0 0.3 0:15.16 /usr/bin/nm-applet
1594 poirrier 20 0 1356M 105M 81000 S 0.0 0.7 0:13.93 /usr/bin/pcmanfm-qt --desktop --profile=lxqt
F1Help F2Setup F3Search F4Filter F5Tree F6SortBy F7Nice - F8Nice + F9Kill F10Quit

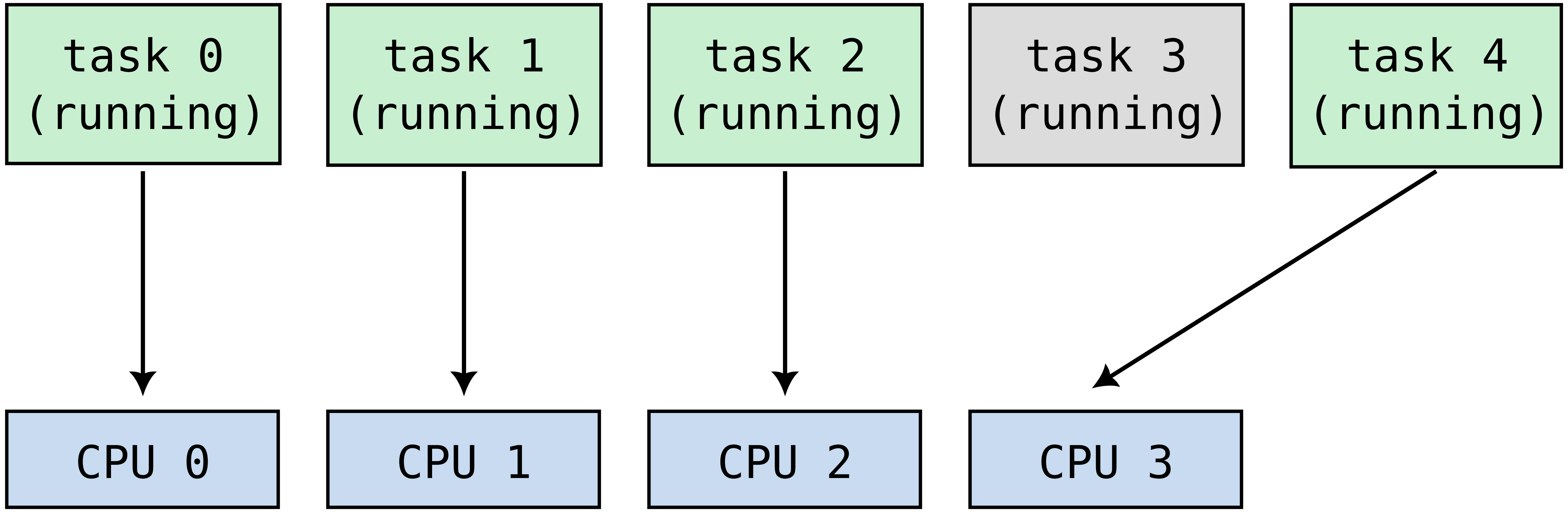
Multitasking on a multi-core processor



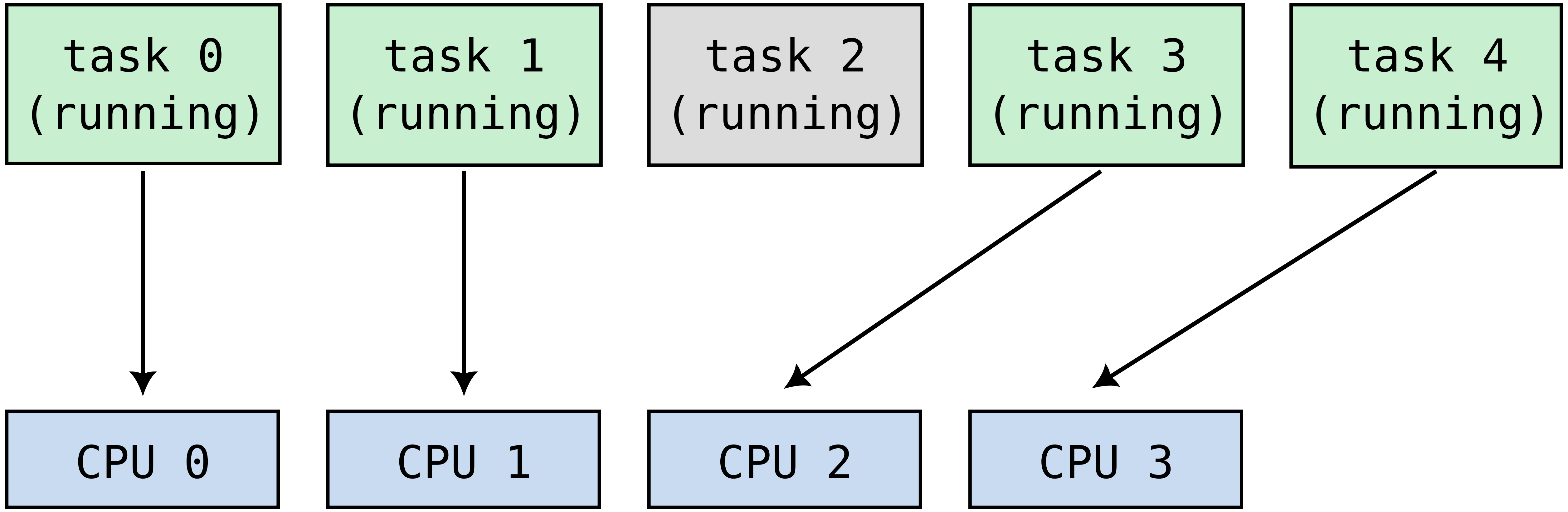
Multitasking on a multi-core processor



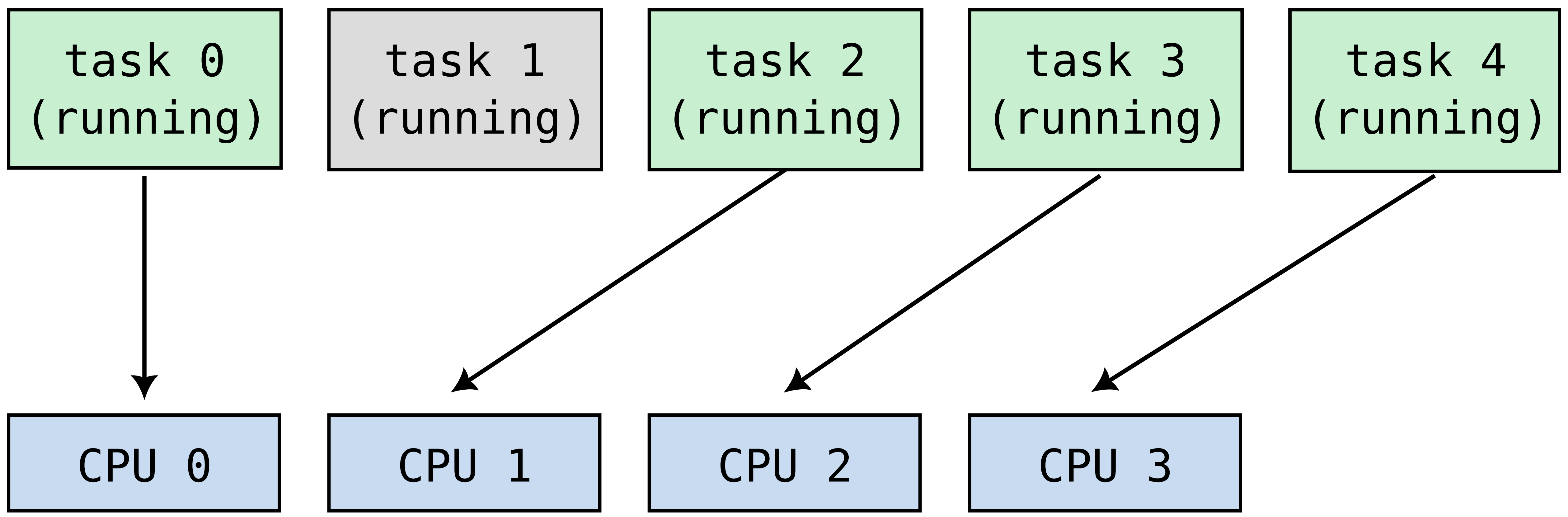
Multitasking on a multi-core processor



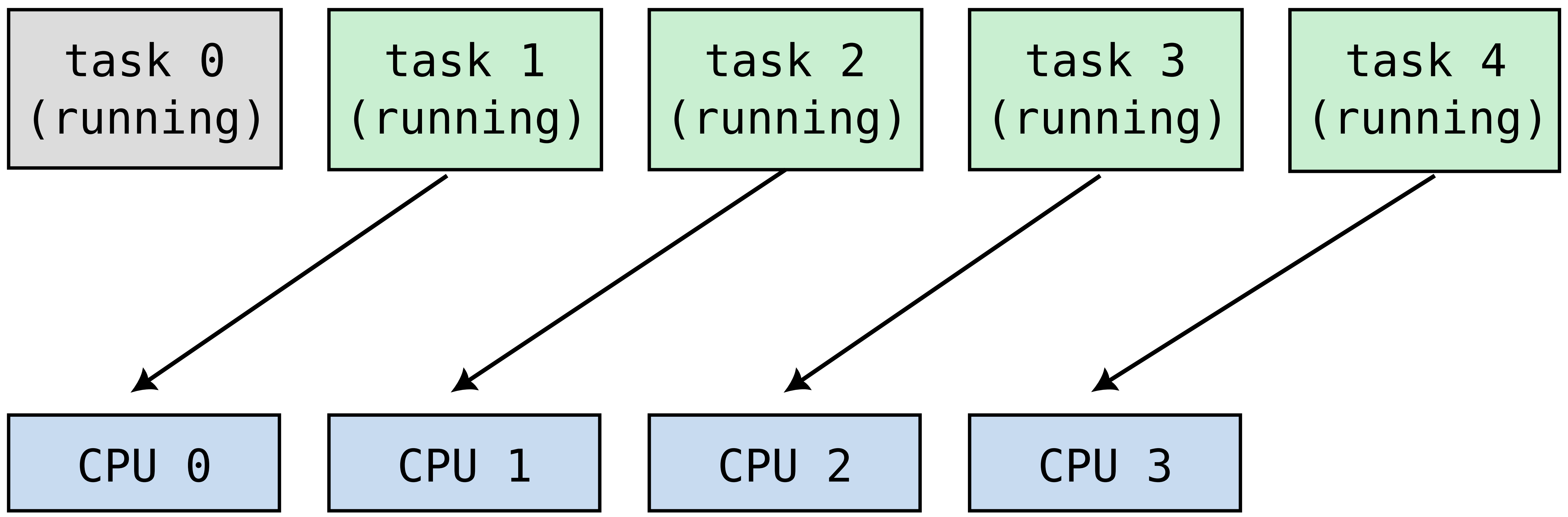
Multitasking on a multi-core processor



Multitasking on a multi-core processor



Multitasking on a multi-core processor



- From a hardware perspective:
  - A CPU corresponds to a single integrated circuit (“IC”) package
  - A computer can (rarely) have multiple CPUs

    Typically only found in datacenters, rarely more than 2
  - Each CPU can have multiple **cores**
    - generally 2-8 cores on laptops
    - up to 128 on datacenter CPUs

- From a software perspective:
  - Everything that can run a task is generally called a “CPU”
  - Only the kernel’s scheduler will (sometimes) care about CPU vs. core
  - All other software is unaware of the difference

- a CPU can have multiple copies of some logic blocks
- very common for arithmetic and logic units (ALUs)

```
                    -
                    -
                    -
ALU 1    ___________________    ___________________    ALU 2
memory   ___________________
         mov rax, [rsi]
         add rcx, rbx
         add rdx, rdi
```

Simultaneous Multithreading (SMT)

- From a hardware perspective:
  - With Simultaneous Multithreading (SMT) (a.k.a. Hyperthreading),
    - each core can run multiple (generally 2) tasks (“threads”)
    - but they share many logic blocks (in particular ALUs)
    - SMT works well when those logic blocks would otherwise be idle
    - SMT is ineffective when those logic blocks are the bottleneck

- From a software perspective:
  - Everything that can run a task is generally called a “CPU”
  - Only the kernel’s scheduler will (sometimes) care about CPU vs. core vs. **thread**
  - All other software is unaware of the difference
  - “Thread” has a different meaning in software

1. SIMD

SIMD

- SIMD stands for Single Instruction Multiple Data
- new, larger registers (in addition to the general purpose ones): "**vector** registers"

bits	255..224	223…192	191…160	159…128	127…96	95…64	63…32	31…0
256	ymm0							
64	fp64 #3		fp64 #2		fp64 #1		fp64 #0	
32	fp32 #7	fp32 #6	fp32 #5	fp32 #4	fp32 #3	fp32 #2	fp32 #1	fp32 #0
16								
8								

- **but**
  - SIMD registers cannot be treated as big integers

- individual “**lanes**” (8-, 16-, 32- or 64-bit parts) generally cannot be accessed individually

SIMD registers

- On Intel (and AMD) ISAs:
  - SSE (~1999): 8 128-bit registers `xmm0` - `xmm7`
  - AVX (~2011): 16 256-bit registers `ymm0` - `ymm15`
  - AVX-512 (~2016, but not yet common): 32 512-bit registers `zmm0` - `zmm31`

- On ARM:
  - Neon (~2005): 16 128-bit registers `Q0` - `Q15`

Example

```c
void add_one(float v[4])
{
    v[0] += 1.0;
    v[1] += 1.0;
    v[2] += 1.0;
    v[3] += 1.0;
}
```

```asm
add_one:
        vbroadcastss    xmm0, DWORD PTR .LC1[rip]         # xmm0 <- { 1.0, 1.0, 1.0, 1.0 }
        vaddps          xmm0, xmm0, XMMWORD PTR [rdi]     # xmm0 <- xmm0 + [v]     (4x 32-bits)
        vmovups         XMMWORD PTR [rdi], xmm0           # [v] <- xmm0
        ret
```

Counter-example

```c
void many_ops(float v[4])
{
    v[0] += 1.0;
    v[1] -= 2.0;
    v[2] *= 3.0;
    v[3] /= v[2];
}
```

```
many_ops:
        vmovss  xmm1, DWORD PTR .LC0[rip]
        vmovss  xmm3, DWORD PTR [rdi+12]
        vmulss  xmm1, xmm1, DWORD PTR [rdi+8]       # <---
        MUL
        vmovss  xmm2, DWORD PTR [rdi+4]
        vmovss  xmm0, DWORD PTR .LC1[rip]
        vsubss  xmm2, xmm2, DWORD PTR .LC2[rip]     # <---
        SUB
        vaddss  xmm0, xmm0, DWORD PTR [rdi]         # <---
        ADD
        vdivss  xmm3, xmm3, xmm1                    # <---
        DIV
        vunpcklps       xmm0, xmm0, xmm2
        vunpcklps       xmm1, xmm1, xmm3
        vmovlhps        xmm0, xmm0, xmm1
        vmovups XMMWORD PTR [rdi], xmm0
        ret
```

This code cannot by performed by a single SIMD instruction

How to use SIMD

- Rely on compilers ("autovectorization")
- Write assembly code
- Use compiler "intrinsics"
  - Intrinsics look like C functions

    but the compiler knows how to translate them to specific assembly code
  - > Intel intrinsics guide
  - > ARM intrinsics

```
for (int x = kx; x < nx; x++) {
    __m256d v = _mm256_andnot_pd(sign, gx[x]);
    __m256d oldmax = maxv[x];
    __m256d newmax = _mm256_max_pd(oldmax, v);
    __m256i keep = _mm256_castpd_si256(_mm256_cmp_pd(oldmax, newmax, _CMP_EQ_OQ));

    maxv[x] = newmax;
    maxi[x] = _mm256_or_si256(_mm256_and_si256(keep, maxi[x]), _mm256_andnot_si256(keep, ix));
}
```

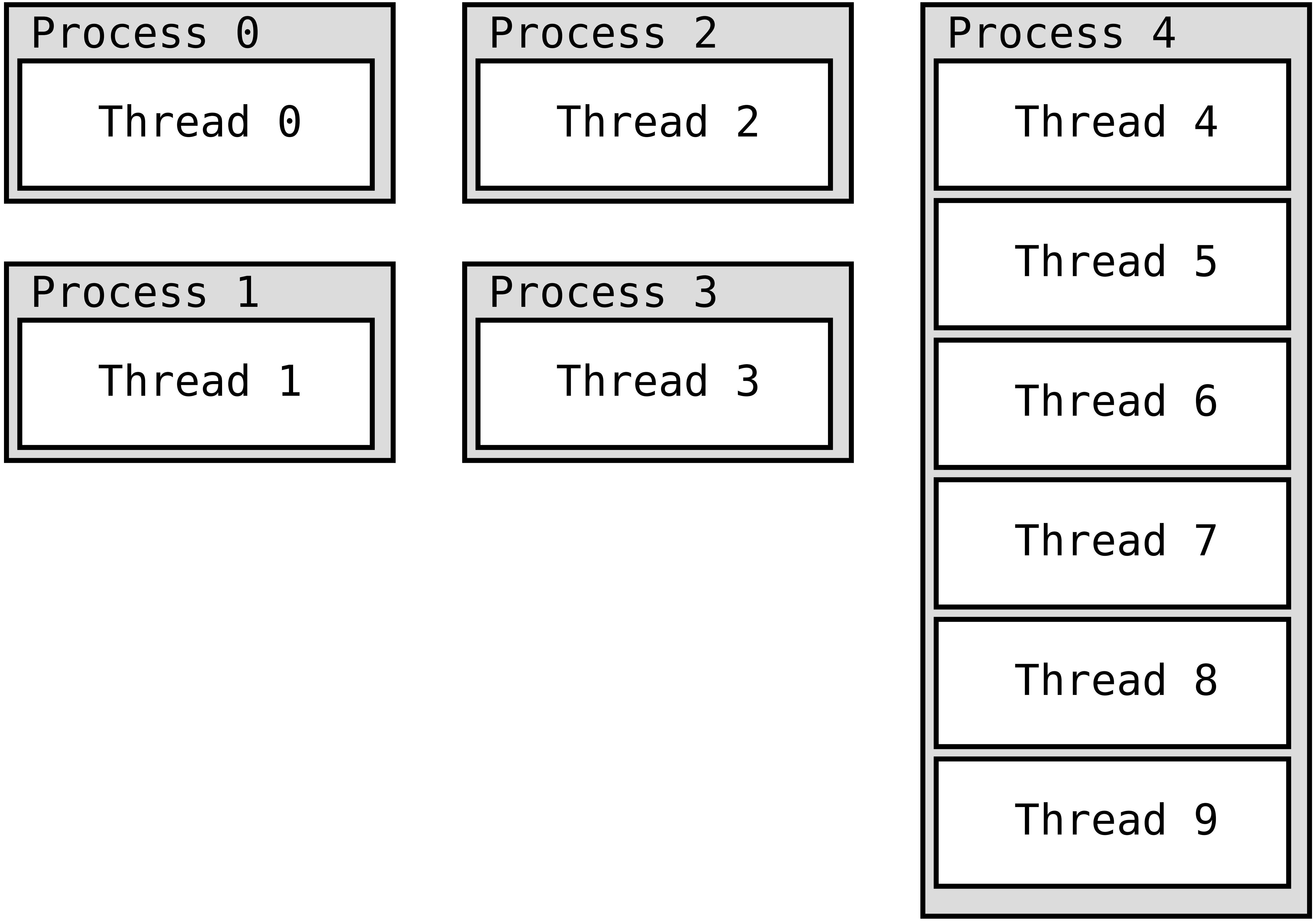
> refer to the intrinsics guide

2. Thread-level concurrency

Processes and threads

- When the OS runs an executable, it gets its own **process**
- A single executable (if run multiple times) can have multiple independent processes
- Memory is virtualized: each process has its own view of the memory it owns

- A process can create (“spawn”) multiple **threads**
- Like processes, each thread is an individual task from the point of view of the scheduler
- Within a process, threads share a same view of the process memory


Process 0
Thread 0
Process 1
Thread 1
Process 2
Thread 2
Process 3
Thread 3
Process 4
Thread 4
Thread 5
Thread 6
Thread 7
Thread 8
Thread 9

- Pro: Communication between threads is extremely efficient
  - Just write something to memory,
  - let other threads read it through the same pointer

- Con: Because memory is shared, **synchronizing** threads is very complex

Wrong code (1)

```
int ready = 0;       //  one if there is some data in the buffer, zero otherwise
int buffer = 0;      //  data in the buffer

// Every push()ed element must be pop()ed exactly once.
// - push() will block until the buffer is empty/available/"not ready"
// - pop() will block until the buffer is nonempty/"ready"
void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    ready = 0;
    return buffer;
}
```

The C compiler is free to reorder this:

```c
void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

into this:

```c
void push(int value)
{
    buffer = value;

    while (ready == 1) {
        // wait
    }

    ready = 1;
}
```

```c
while (ready == 1) {
    // wait
}
```

The C compiler can also notice that this loop has either

- zero iterations, or
- infinitely many iterations without side effects (UB!)

thus remove the loop!

Wrong code (2)

```c
volatile int ready = 0;       //  one if there is some data in the buffer, zero otherwise
volatile int buffer = 0;      //  data in the buffer

void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    ready = 0;
    return buffer;
}
```

Thread 0

```
                            // ready = 1      buffer = 'A'
int pop()
{
    while (ready == 0) {
        // wait
    }
                            // ready = 1      buffer = 'A'
    ready = 0;              // ready = 0      buffer = 'A'







                            // ready = 0      buffer = 'B'
                            // ready = 1      buffer = 'B'


    return buffer;
}
```

Thread 1

```
void push(int value)                 // push('B')
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

Wrong code (3)

```
volatile int ready = 0;      //  one if there is some data in the buffer, zero otherwise
volatile int buffer = 0;     //  data in the buffer

void push(int value)
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}

int pop()
{
    while (ready == 0) {
        // wait
    }

    int b = buffer;
    ready = 0;
    return b;
}
```

Thread 0

```
                                   // ready = 0      buffer = 'X'
void push(int value)  // push('A')
{
    while (ready == 1) {
        // wait
    }
                                   // ready = 0      buffer = 'X'




                                   // ready = 0      buffer = 'B'
                                   // ready = 1      buffer = 'B'


    buffer = value;                // ready = 1      buffer = 'A'
    ready = 1;                     // ready = 1      buffer = 'A'
}
```

Thread 1

```
void push(int value)   // push('B')
{
    while (ready == 1) {
        // wait
    }

    buffer = value;
    ready = 1;
}
```

Solution

- low-level: compiler intrinsics for "**atomic**" operations:

  combined operations that are performed as a single unit

  no thread will ever see the memory in an intermediate state

- high-level: use libraries that correctly implement some primitives:

  locks, queues, etc.

  - Posix threads ("`pthreads`"; Linux, MacOS)
  - OpenMP (Open Multi-Processing; portable)

3. Distributed computing

Distributed computing

- In distributed computing, processes do not share memory
- They must communicate by explicitly sending data to each other

  (`send()`, `recv()`, etc.)

  typically over the network

Distributed computing

- Con: Communication is much slower than multithreading

- Pros:
  - Easier to implement and reason about
  - Scales to higher levels of parallelism
    - As of today, off-the-shelf computers can have up to

      2 processors × 128 cores × 2 SMT threads = 512 concurrent software threads
    - With distributed computing, networked computers can work together in parallel

- Libraries:
  - Message Passing Interface (MPI)
  - …

4. Hardware acceleration

Graphics processing units (GPUs)

- GPUs were designed to perform the same simple, repetitive operations
  - on many pixels ("fragment shaders"), or
  - on many 3D coordinates ("vertex shaders")

Simplified fragment shader example

Given:

- the coordinates `(i, j)` of a pixel on screen
- the corresponding coordinates in 3D space `(x, y, z)`
- the normal vector to the surface at that point `(v0, v1, v2)`
- the texture color for that point `(r, g, b)`
- the coordinates `(lx, ly, lz)` and color `(lr, lg, lb)` of a light source

compute

- the apparent color of the pixel.

Simplified vertex shader example

Given:

- the coordinates of an object in 3D space `(x, y, z)`
- the coordinates of the viewpoint camera in 3D space `(vx, vy, vz)`
- the viewpoint camera orientation `(q0, q1, q2, q2)`
- the viewpoint camera's focal length `f`

compute:

- the coordinates `(i, j)` of this object on screen.

- GPUs were designed to perform the same simple, repetitive operations
    - on many pixels ("fragment shaders"), or
    - on many 3D coordinates ("vertex shaders")
- they generally adopt a SIMT ("single instruction, multiple threads") model
    - hundreds of threads working on different sets of data
    - but running the exact same instructions

      (in CUDA, the 32 threads in a "warp" execute in lockstep)
- good fit for long loops performing repetitive operations
- bad fit for if/then/else

Single instruction, multiple threads (SIMT)

```
#                                                                         Warp
#                                                  Thread 0            Thread 1            Thread 2            Thread 3
#                                              ------------------  ------------------  ------------------  ------------------
#                                               condition = True    condition = True    condition = False   condition = False
def function(condition, data):
    if condition:
        r = a(data)
    else:
        r = b(data)
    return r
```

Single instruction, multiple threads (SIMT)

```
#                                                                           Warp
#                                                    Thread 0           Thread 1           Thread 2             Thread 3
#                                                ------------------ ------------------ ------------------- -------------------
#                                                 condition = True   condition = True   condition = False    condition = False
def function(condition, data):
    if condition:                                if True:           if True:           if False:            if False:
        # <-----
        r = a(data)
    else:
        r = b(data)
    return r
```

Single instruction, multiple threads (SIMT)

```
#                                                             Warp
#                                        Thread 0           Thread 1           Thread 2             Thread 3
#                                    ------------------ ------------------ ------------------- -------------------
#                                     condition = True   condition = True   condition = False    condition = False
def function(condition, data):
    if condition:                    if True:           if True:           if False:            if False:
        r = a(data)                      r = a(data)        r = a(data)        pass                 pass
        # <-----
    else:
        r = b(data)
    return r
```

Single instruction, multiple threads (SIMT)

```
#                                                                        Warp
#                                         Thread 0                 Thread 1                 Thread 2                  Thread 3
#                                    ------------------  ------------------  -------------------  -------------------
#                                     condition = True    condition = True    condition = False    condition = False
def function(condition, data):
    if condition:                        if True:            if True:            if False:            if False:
        r = a(data)                          r = a(data)         r = a(data)         pass                 pass
    else:                                else:               else:               else:                else:
         # <-----
        r = b(data)
    return r
```

Single instruction, multiple threads (SIMT)

```
#                                                                      Warp
#                                                  Thread 0           Thread 1           Thread 2             Thread 3
#                                             ------------------ ------------------ ------------------- -------------------
#                                              condition = True   condition = True   condition = False   condition = False
def function(condition, data):
    if condition:                             if True:           if True:           if False:           if False:
        r = a(data)                               r = a(data)        r = a(data)        pass                pass
    else:                                     else:              else:              else:               else:
        r = b(data)                               pass               pass               r = b(data)         r = b(data)
        # <-----
    return r
```

Single instruction, multiple threads (SIMT)

```
#                                                                                Warp
#                                                     Thread 0               Thread 1               Thread 2                Thread 3
#                                                  ------------------    ------------------    -------------------    -------------------
#                                                   condition = True      condition = True      condition = False       condition = False
def function(condition, data):
    if condition:                                  if True:               if True:               if False:               if False:
        r = a(data)                                    r = a(data)            r = a(data)            pass                    pass
    else:                                          else:                  else:                  else:                   else:
        r = b(data)                                    pass                   pass                   r = b(data)             r = b(data)
    return r                                       return r               return r               return r                return r
        # <-----
```

Single instruction, multiple threads (SIMT)

```
#                                                                           Warp
#                                               Thread 0           Thread 1           Thread 2            Thread 3
#                                           ------------------ ------------------ ------------------- -------------------
#                                            condition = True   condition = True   condition = False   condition = False
def function(condition, data):
    if condition:                           if True:           if True:           if False:           if False:
        r = a(data)                             r = a(data)        r = a(data)        pass                pass
    else:                                   else:              else:              else:               else:
        r = b(data)                             pass               pass               r = b(data)         r = b(data)
    return r                                return r           return r           return r            return r
```

How do we use GPUs?

- GPUs are programmed in special-purpose languages

- Typically, all GPU code is compiled
  - during application startup (“shader compliation”),
  - by the device driver
  - for the specific GPU device installed (amount and subdivision of threads, memory, etc.)

- Two dominant players in the GPU market: nVidia and AMD

- Three major general-purpose GPU programming languages:
  - CUDA (nVidia, proprietary)
  - ROCm (AMD, open-source)
  - OpenCL (cross-platform, open-source)

Examples (GLSL)

```
float box(in vec2 st, in vec2 size){
    size = vec2(0.5) - size*0.5;
    vec2 uv = smoothstep(size,
                        size+vec2(0.001),
                        st);
    uv *= smoothstep(size,
                    size+vec2(0.001),
                    vec2(1.0)-st);
    return uv.x*uv.y;
}
```

Examples (GLSL)

```
vec3 rgb2hsb( in vec3 c ){
    vec4 K = vec4(0.0, -1.0 / 3.0, 2.0 / 3.0, -1.0);
    vec4 p = mix(vec4(c.bg, K.wz),
                 vec4(c.gb, K.xy),
                 step(c.b, c.g));
    vec4 q = mix(vec4(p.xyw, c.r),
                 vec4(c.r, p.yzx),
                 step(p.x, c.r));
    float d = q.x - min(q.w, q.y);
    float e = 1.0e-10;
    return vec3(abs(q.z + (q.w - q.y) / (6.0 * d + e)),
                d / (q.x + e),
                q.x);
}
```

Examples (CUDA)

```
inline __device__ float3 roundAndExpand(float3 v, ushort *w) {
  v.x = rintf(__saturatef(v.x) * 31.0f);
  v.y = rintf(__saturatef(v.y) * 63.0f);
  v.z = rintf(__saturatef(v.z) * 31.0f);

  *w = ((ushort)v.x << 11) | ((ushort)v.y << 5) | (ushort)v.z;
  v.x *= 0.03227752766457f;  // approximate integer bit expansion.
  v.y *= 0.01583151765563f;
  v.z *= 0.03227752766457f;
  return v;
}
```

Parallel matrix multiplication

```
8192 x 8192 matrix multiplication
precision: fp32 (“float”) - total 256 MB per matrix
CPU: Ryzen 7900 x3d (released Feb 2023)
```

version	description	seconds	ratio	improvement
matmul_1	straightforward implementation	2794.068	**1x**	
matmul_2	transpose B matrix	338.163	8x	8x
matmul_3	block multiply	79.346	35x	5x
matmul_4	AVX512 SIMD	14.121	198x	6x
matmul_5	OpenBLAS	7.462	374x	2x
matmul_6	OpenBLAS, 24 threads	1.114	2508x	7x

Parallel matrix multiplication

```
65536 x 65536 matrix multiplication
precision: fp32 (“float”) - total 16 GB per matrix
CPU: Ryzen 7900 x3d (released Feb 2023)
GPU: nVidia H100 80GB (released Sep 2022)
```

version	description	seconds	ratio
matmul_6	OpenBLAS, 24 threads, 7900x3d	344.961	**1x**
matmul_7	cuBLAS	28.657	12x