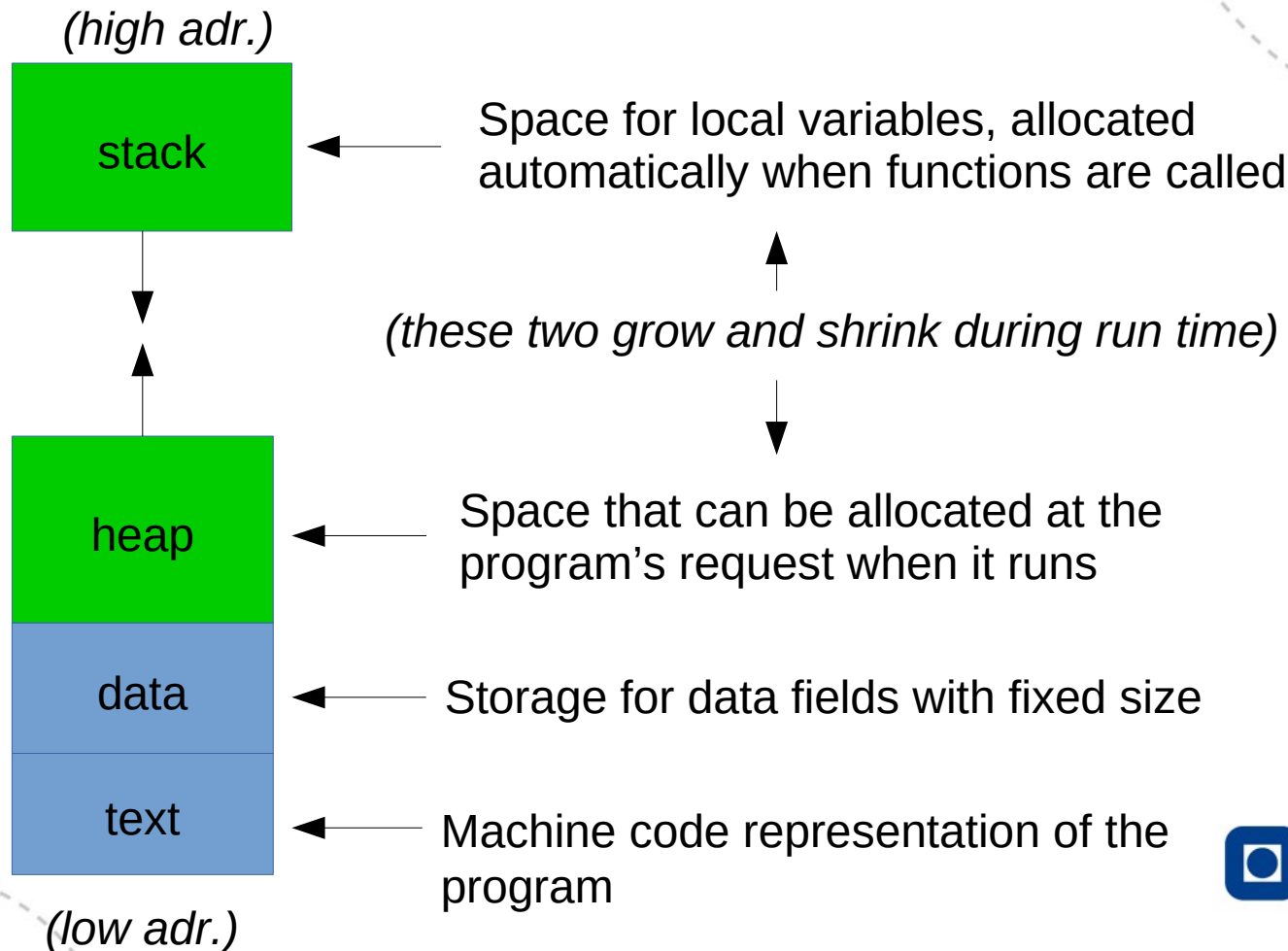




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Pthreads introduction

Back to the process image



The purpose of the stack

- The stack supports function calls:

```
fib (n) {  
    if (n>1)  
        return fib(n-1) + fib(n-2)  
    else  
        return 1  
}
```

```
main() {  
    print fib(2)  
}
```

n=2

Stack



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Anatomy of function calls

```
fib (n) {  
    if (n>1)  
        return fib(n-1) + fib(n-2)  
    else  
        return 1  
}
```

```
main() {  
    print fib(2)  
}
```

1
n = 1
n = 2

Stack



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Anatomy of function calls

1
n = 0
fib(1) = 1
n = 2

Stack

```
fib (n) {  
    if (n>1)  
        return fib(n-1) + fib(n-2)  
    else  
        return 1  
}  
  
main() {  
    print fib(2)  
}
```



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Anatomy of function calls

```
fib (n) {  
    if (n>1)  
        return fib(n-1) + fib(n-2)  
    else  
        return 1  
}
```

```
main() {  
    print fib(2)  
}
```

1 + 1 = 2
fib(2) = 1
fib(1) = 1
n = 2

Stack



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Anatomy of function calls

```
fib (n) {  
    if (n>1)  
        return fib(n-1) + fib(n-2)  
    else  
        return 1  
}
```

```
main() {  
    print fib(2)  
}
```

2

Stack

...and the number "2" appears on screen.



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The purpose of the heap

- The heap supports explicit program allocations:

```
*buffer = 0  
main() {  
    buffer = allocate (7)  
    buffer[0] = 'H'  
    buffer[1] = 'e'  
    buffer[2] = 'l'  
    buffer[3] = 'l'  
    buffer[4] = 'o'  
    buffer[5] = '!'  
    buffer[6] = 0  
    print ( buffer )  
    deallocate( buffer )  
}
```

buffer = 0

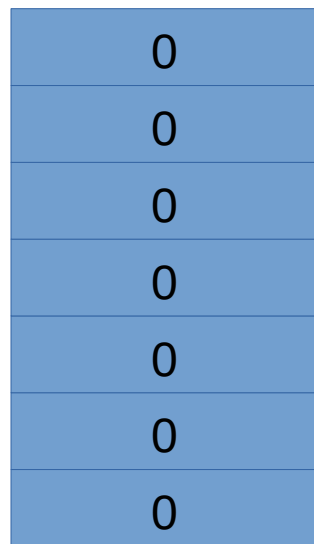
Heap

Data segment



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Anatomy of an explicit allocation



Heap

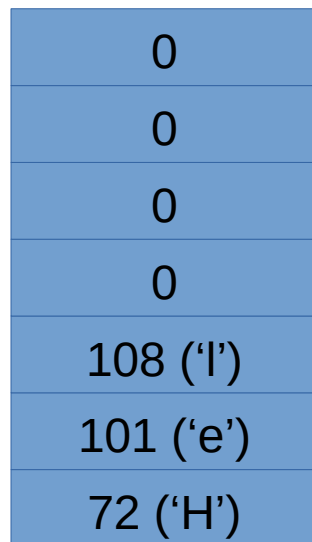
buffer = 8192

Data segment

```
*buffer = 0
main() {
    buffer = allocate (7)
    buffer[0] = 'H'
    buffer[1] = 'e'
    buffer[2] = 'l'
    buffer[3] = 'l'
    buffer[4] = 'o'
    buffer[5] = '!'
    buffer[6] = 0
    print ( buffer )
    deallocate( buffer )
}
```

(this number is an arbitrary address inside the range of the heap)

Anatomy of an explicit allocation



Heap

buffer = 8192

Data segment

```
*buffer = 0
main() {
    buffer = allocate (7)
    buffer[0] = 'H'
    buffer[1] = 'e'
    buffer[2] = 'l'
    buffer[3] = 'l'
    buffer[4] = 'o'
    buffer[5] = '!'
    buffer[6] = 0
    print ( buffer )
    deallocate( buffer )
}
```



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Anatomy of an explicit allocation

0
33 ('!')
111 ('o')
108 ('l')
108 ('l')
101 ('e')
72 ('H')

Heap

buffer = 8192

Data segment

```
*buffer = 0
main() {
    buffer = allocate (7)
    buffer[0] = 'H'
    buffer[1] = 'e'
    buffer[2] = 'l'
    buffer[3] = 'l'
    buffer[4] = 'o'
    buffer[5] = 'l'
    buffer[6] = 0
    print ( buffer )
    deallocate( buffer )
}
```



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Anatomy of an explicit allocation

0
33 ('!')
111 ('o')
108 ('l')
108 ('l')
101 ('e')
72 ('H')

Heap

buffer = 8192

Data segment

```
*buffer = 0
main() {
    buffer = allocate (7)
    buffer[0] = 'H'
    buffer[1] = 'e'
    buffer[2] = 'l'
    buffer[3] = 'l'
    buffer[4] = 'o'
    buffer[5] = '!'
    buffer[6] = 0
    print ( buffer )
    deallocate( buffer )
}
```

"Hello!" appears on screen

Anatomy of an explicit allocation

```
*buffer = 0
main() {
    buffer = allocate (7)
    buffer[0] = 'H'
    buffer[1] = 'e'
    buffer[2] = 'l'
    buffer[3] = 'l'
    buffer[4] = 'o'
    buffer[5] = '!'
    buffer[6] = 0
    print ( buffer )
    deallocate( buffer )
}
```

buffer = 8192

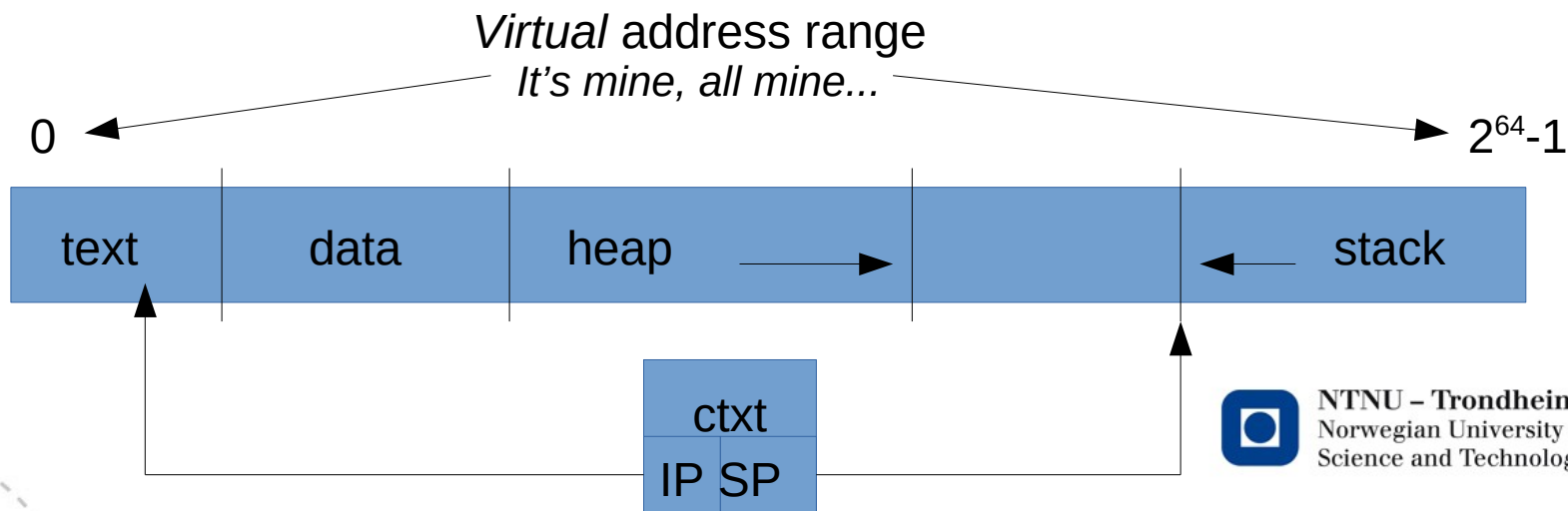
Heap

Data segment

Memory at 8192 can be re-used
for a different allocation later

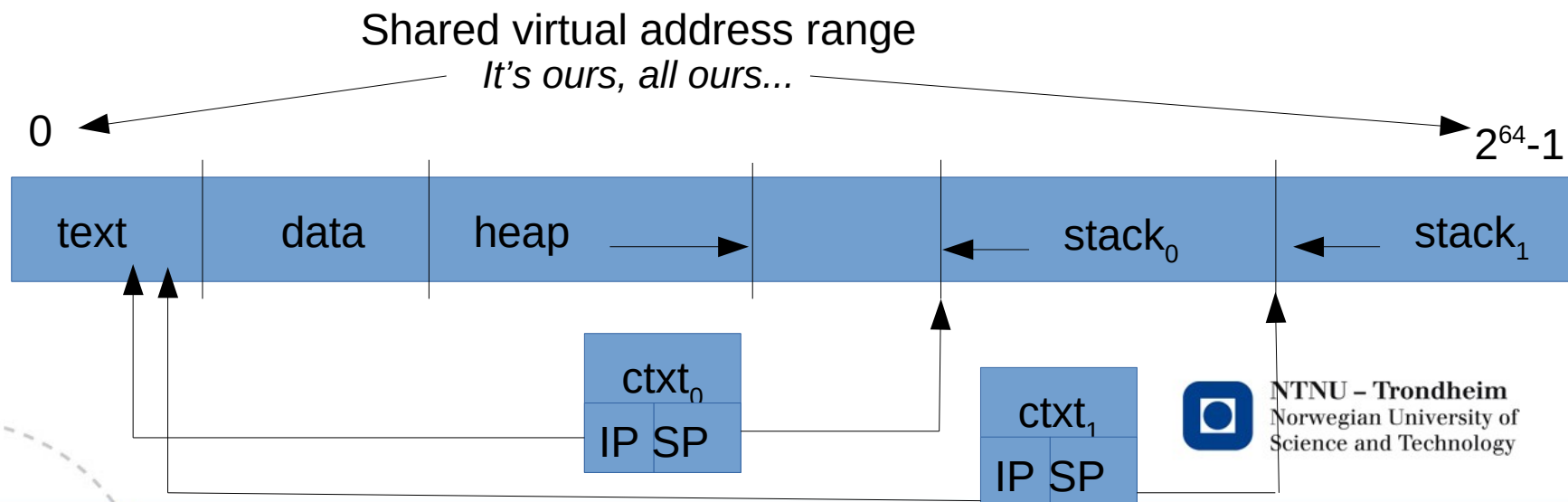
One process and its thread

- In a sequential program, we follow one path through the program text
- It's enough to have 1 of everything we have examined so far:



One process and two threads

- In a threaded program, we follow several independent paths through the program text
- This requires each thread to track its position, and the state of its own stack
- Data and heap segments are shared between these contexts, so if one thread alters a variable stored on the heap, that variable changes value for the other thread also



The concept of concurrency

- The central idea is that we can improve programs by relaxing the restriction that their statements must only ever be executed in 1 specific order
- This can be done in many ways, and at many different levels of abstraction
 - “*one step of the program*” might mean one database transaction, one web page served, one image rendered, *etc. etc.*
- When our goal is to compute some number, individual machine operations make a natural unit step, so that we can rearrange the calculation in detail



Software that enables concurrency

- Threads are a software construct
 - They only augment the program with information about which steps depend on a fixed sequence, and which ones don't
- The hardware and O/S get to decide whether or not to do anything with that information
 - Among the many valid execution orders of a threaded program, there is still the option of running all parts one after the other, like a sequential program
- For (TDT4200) *parallel computing*, we would like to have a maximal number of operations executed simultaneously

The hardware that executes our program

- Mapping of threads to physical processing cores is trivial when you have the same number of threads and cores
- *Oversubscription* can occasionally be useful
 - It can keep the cores occupied when some threads need to block because they're waiting for resources
 - It is absolutely instrumental to using GPUs effectively, which we can return to later on
- For applications where the threads are constantly calculating something, multiple threads per core only delay the computation by adding the overhead of scheduling switches between them



Shared memory parallelism

- A set of thread contexts map onto a set of processing cores
 - Often a 1-1 mapping, but not by necessity
- Each thread has its own private work space
 - That is, the local variables in the stack space of its function call(s)
- All threads have a shared, global workspace
 - The data and heap segments can be used for inter-thread communication and collaboration



What could possibly go wrong?



- Any shared work space can become an arena for conflicts
 - These are often caused by disagreements over the management of shared resources
- Parallel computers don't grow sentimental about such conflicts, but they can still have them
 - What if two (or more) independent threads simultaneously try to assign a number to a shared memory location?
- We must decide on some kind of contract or policy to resolve these situations



Theoretically speaking

- The PRAM model* is a minimalistic, abstract machine which proposes 4 candidate policies:
 - *Common Value* admits the assignment and allows execution to proceed if (and only if) all attempts to make it are trying to assign the same value
 - *Arbitrary Value* assigns the value from one of the attempts, and the program must assume that it can be any of them
 - *Priority* requires each thread to have a ranking among its peers, and the highest ranked assignment wins
 - *Reduction* assigns the result of applying some commutative operation to all the attempts (sum, product, logical AND, etc.)



Practically speaking

- The only policy I have ever seen realized in actual hardware is the *Arbitrary Value* policy
- The value is simply determined by handling the assignments in the order they arrive at the memory banks
- This makes the program
 - Behave non-deterministically in the best case
 - Crash and Burn™ in the worst (and by far most common) case



The *Read-Modify-Write* cycle

(again)

- We talked about this in the context of the von Neumann computer, but I'm repeating it now
- A minimal statement in a programming language might look like this:

```
total_sum += my_value;
```
- After the compiler is finished with it, we get a short sequence of smaller operations, *e.g.*

```
load my_value into register B  
load total_sum into register A  
add register B to register A  
store register A in total_sum
```
- Programs produce this pattern all the time



Off to the races

- Suppose we have two threads with different numbers (4,6) as their private versions of `my_value`
- We want their sum (10) in a shared location
- If we try to run their `total_sum += my_value` statements simultaneously
(or even just *almost* simultaneously)

the answer comes out wrong:

Time step	total_sum	my_value #1	Thread #1	my_value #2	Thread #2
1	0	4	B ← 4	6	
2	0	4	A ← 0	6	B ← 6
3	0	4	A ← A+B = 4	6	A ← 0
4	4	4	total_sum ← 4	6	A ← A+B = 6
5	6	4		6	total_sum ← 6



Race conditions

- This sort of thing is called a *race condition*
 - So named because just as in a horse race, the result is determined by which participant finishes first
- It can occur when there is contention for any shared thing that requires exclusive access to end well
- When the contested object is the value of a datum in memory, we can also call them *data races*
- The code segment that must not overlap is called a *critical section*



Instruments of protection

- Several mechanisms have been invented to ensure exclusive access in a critical section
 - Atomic operations
 - Load Linked & Store Conditional instructions
 - Mutex (lock) and semaphore data structures
 - Higher-level programming model constructs
- All of these need some hardware support for their underlying operations
 - Well, *almost*...
 - There is actually a short and unreadable 1965 treatment by Dijkstra*, which proves that you can implement mutual exclusion purely in software
 - If you try that method, you will discover that it's dreadfully slow in practice

* *Solution of a problem in Concurrent Programming Control*,
E. W. Dijkstra, Communications of the ACM, Vol. 8, No. 9, 1965



Pthreads are quite minimalistic

- They really only have 5 (or 6) things they can do:
 - Start
 - Stop
 - Set and release a memory lock
 - Wait until some other thread wakes them up
 - Wait for every other thread at a barrier (just like MPI can do with processes)
- It's not super productive to write pthreads code explicitly, because it makes you push many keys on the keyboard in order to solve conceptually simple problems
- We cover them anyway, because OpenMP (our next topic) is mostly implemented in terms of pthread operations if you closely inspect how it works

