[368] C++ Programming: Welcome!

Tyler Caraza-Harter

Outline

Welcome

Logistics

Background and Motivation

- Why C/C++: performance
- Why C++ (over C): language features

Demos

Introductions

Tyler Caraza-Harter

- Long time Badger
- Email: tharter@wisc.edu
- Just call me "Tyler" (he/him)

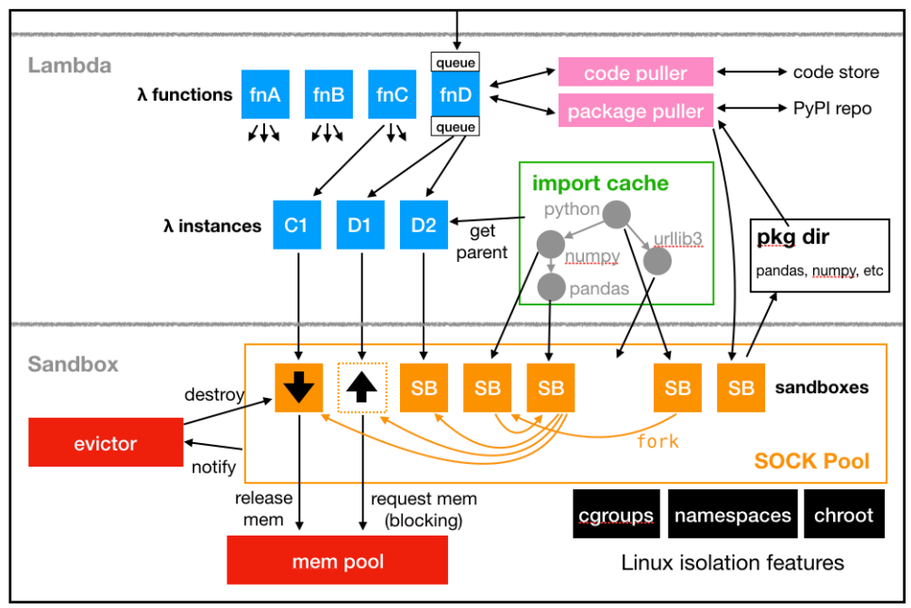
Industry experience

- Worked at Microsoft* on SQL Server and Cloud
- Other internships/collaborations:
  Qualcomm, Google, Facebook*, Tintri*, Bauplan*

*used C++

Open source

- OpenLambda (serverless cloud platform)
- https://github.com/open-lambda/open-lambda



Who are You?

Year in school? Major?

What CS courses have people taken before?

- 300? 320? 354?

Please fill this form (**due today**):
https://forms.gle/3BaLREB1upurZDky6

Why?

- Help me get to know you
- Let me know your GitHub username (create an account if necessary) so I can grade your GitHub classroom submissions.

What will you learn in this 368?

Learning objectives

- Read and understand C++ code
- Write C++ programs making use of the abstractions provided by the language
- Understand the lower level details of memory management like pointers and references
- Organize and build multi-file projects using the make tool
- Solve real world programming problems using C++ as a tool

What will you learn today?

Learning objectives

- recall course logistics and policies
- describe reasons for using a language like C/C++
- describe reasons for using C++ over C

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Main Websites

1. https://tyler.caraza-harter.com/cs368/s24/schedule.html
   - schedule, course content, how to get help
   - links to all other resources/tools
   - some lecture recordings (review only)

2. https://github.com/cs368-wisc/s24
   - project specifications
   - lecture demo code

3. Canvas
   - announcements
   - quizzes
   - grade summaries

Other Tools

4. TopHat (me asking you questions during lecture)
    - can earn points from this

5. Piazza (asking questions of general interest)
    - goal: responses <1 business day
    - don't post >5 lines of project code

6. Email (asking questions of individual interest)
    - goal: responses <2 business days
    - please keep related issues on the same thread

7. GitHub classroom
    - you'll be given a **private** repo for your project

8. Anki Flash Cards
    - memory terms, basic ideas using flash cards and spaced repetition

Lecture

Wednesday:

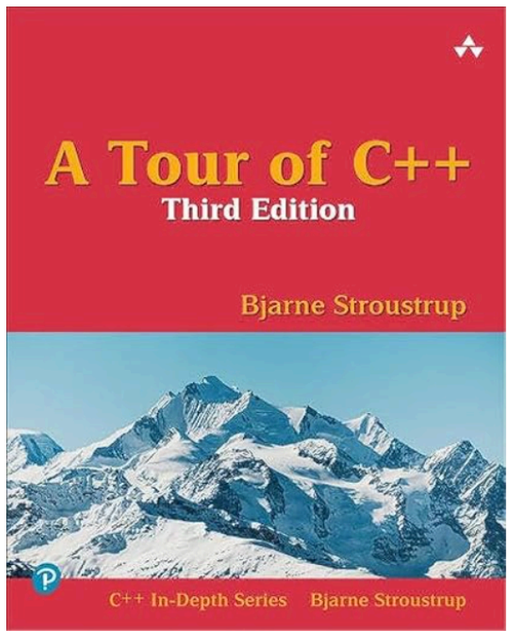
- in person (usually recorded too, barring technical difficulties)
- focus on concepts (lecture, worksheets, etc)
- TopHats

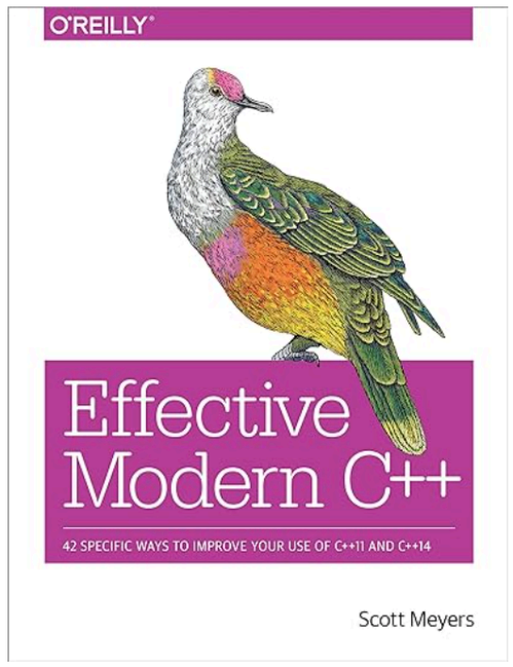
Friday:

- posted online, multiple short videos
- focus on programming demos
- watch before next in-person class!

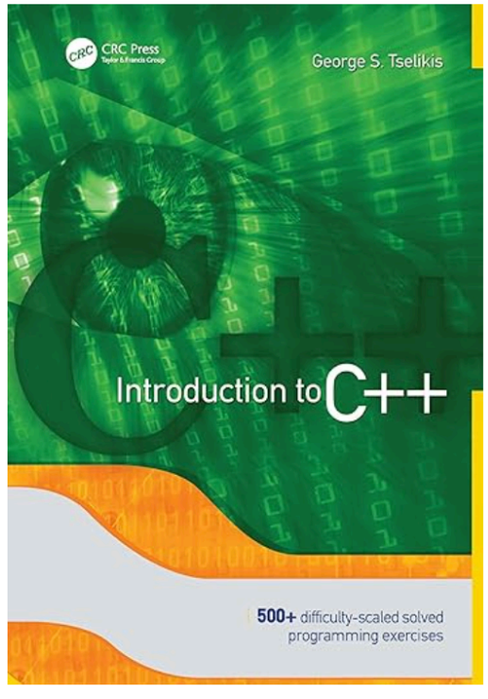
A Few Books (Optional Supplement)

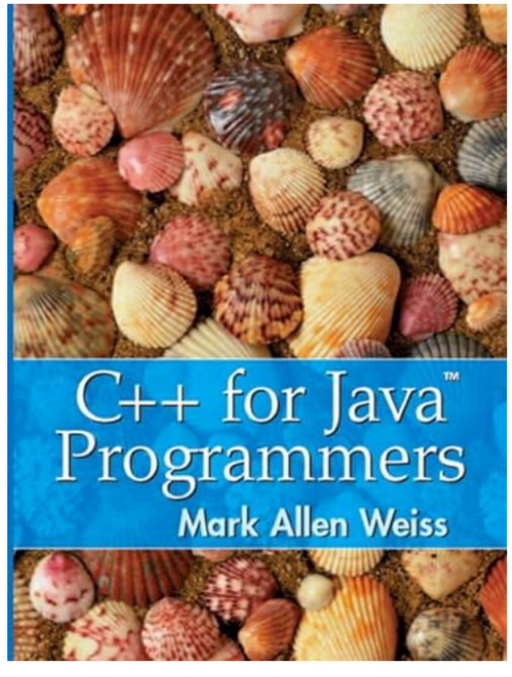
There is no assigned text (will cover everything needed in lecture). But here are a few books to consider if you want to supplement:

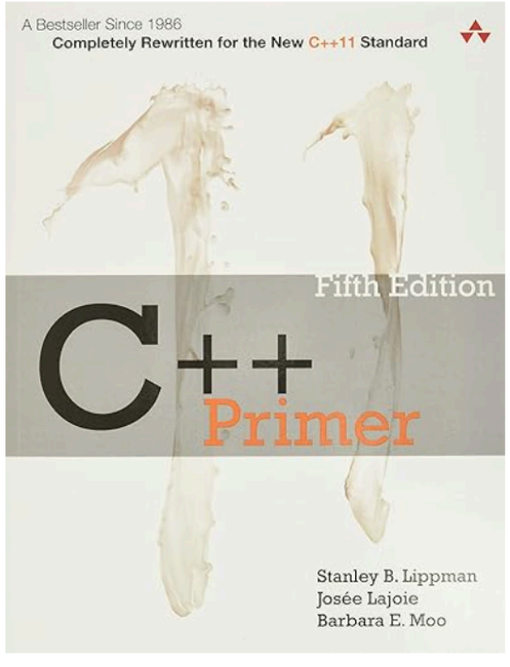




Note: the entire O'Reilly collection is free online through the Madison Public Library using a library card (also free)







Bonus Resource:

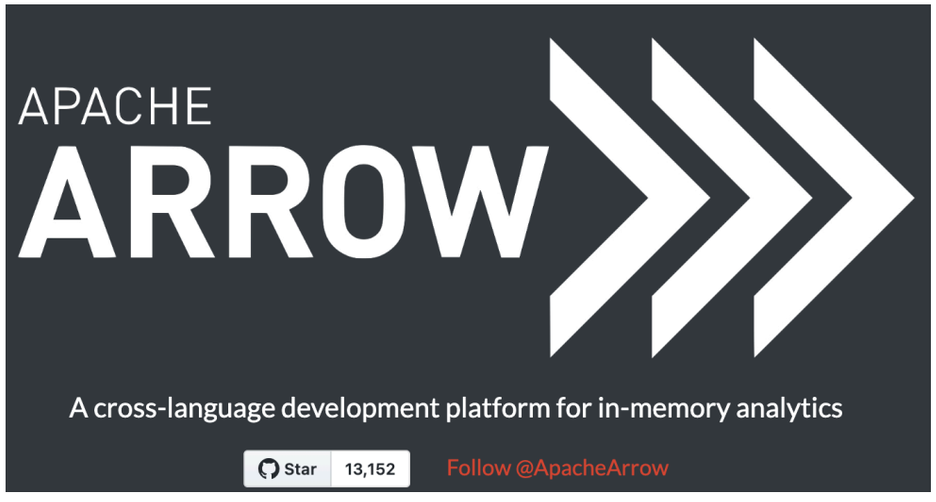
https://www.youtube.com/playlist?list=PLlrATfBNZ98dudnM48yfGUldqGD0S4FFb

Good C++ YouTube series by "The Cherno" if you want to explore other topics beyond this term.

Sparrow Project

Project:

- one big project with six project stages (P1 - P6)
- project name: Sparrow (simple prototype of Arrow)
- Arrow project (https://arrow.apache.org/) enables fast in-memory analytics on tables of data; the main implementation is in C++



Collaboration:

- done individually
- can help each other debug (with citation)
- sharing code is NOT allowed

Submission:

- you will push your code to a GitHub classroom repo (keep it private!)
- submit a form when a specific version (commit number) is ready for grading

Grading:

- autograded using tests I'll release
- I might manually modify grades if anybody tries to "game the tests"

Grading

This course is credit/no credit:

- so pass/fail, no letter grades
- to pass, you need to earn >=100 points
- there will be >150 points possible to earn, so there are many possible ways to pass
- 100 is a low bar; 140+ would be a score to really "feel good" about

Scoring:

- projects: 120 points possible (4 per passed test)
- quizzes: 30 points possible (1 per correct answer)
- TopHat: 1 point for correct answer, 0.5 for incorrect
- other: I might offer other opportunities for points as we go

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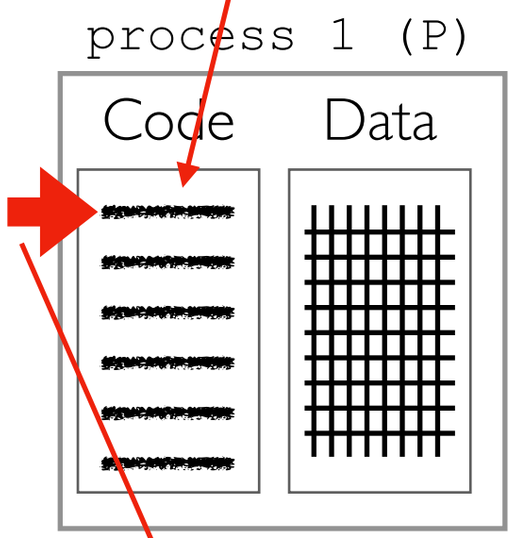
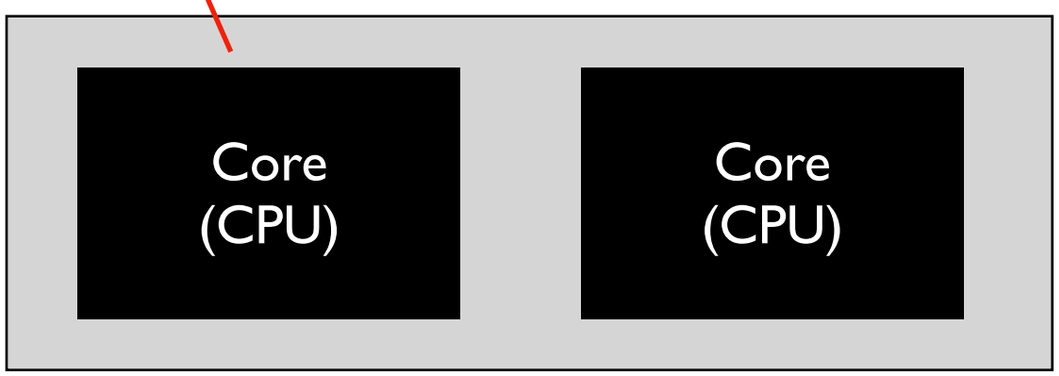
Demos

Background: How to Code Runs on CPUs

these instructions are in "machine code"
that the CPU can understand





Multi-Core Processor (CPU)

https://pages.cs.wisc.edu/~deppeler/cs354/reference/x86-cheat-sheet.pdf

these instructions are
represented as 1's and 0's
the CPU understands

arithmetic
two operand instructions

```
addl src,dst   dst = dst + src
subl src,dst   dst = dst - src
imull src,dst  dst = dst * src
sall src,dst   dst = dst << src (aka shll)
sarl src,dst   dst = dst >> src (arith)
shrl src,dst   dst = dst >> src (logical)
xorl src,dst   dst = dst ^ src
andl src,dst   dst = dst & src
orl src,dst    dst = dst | src
```

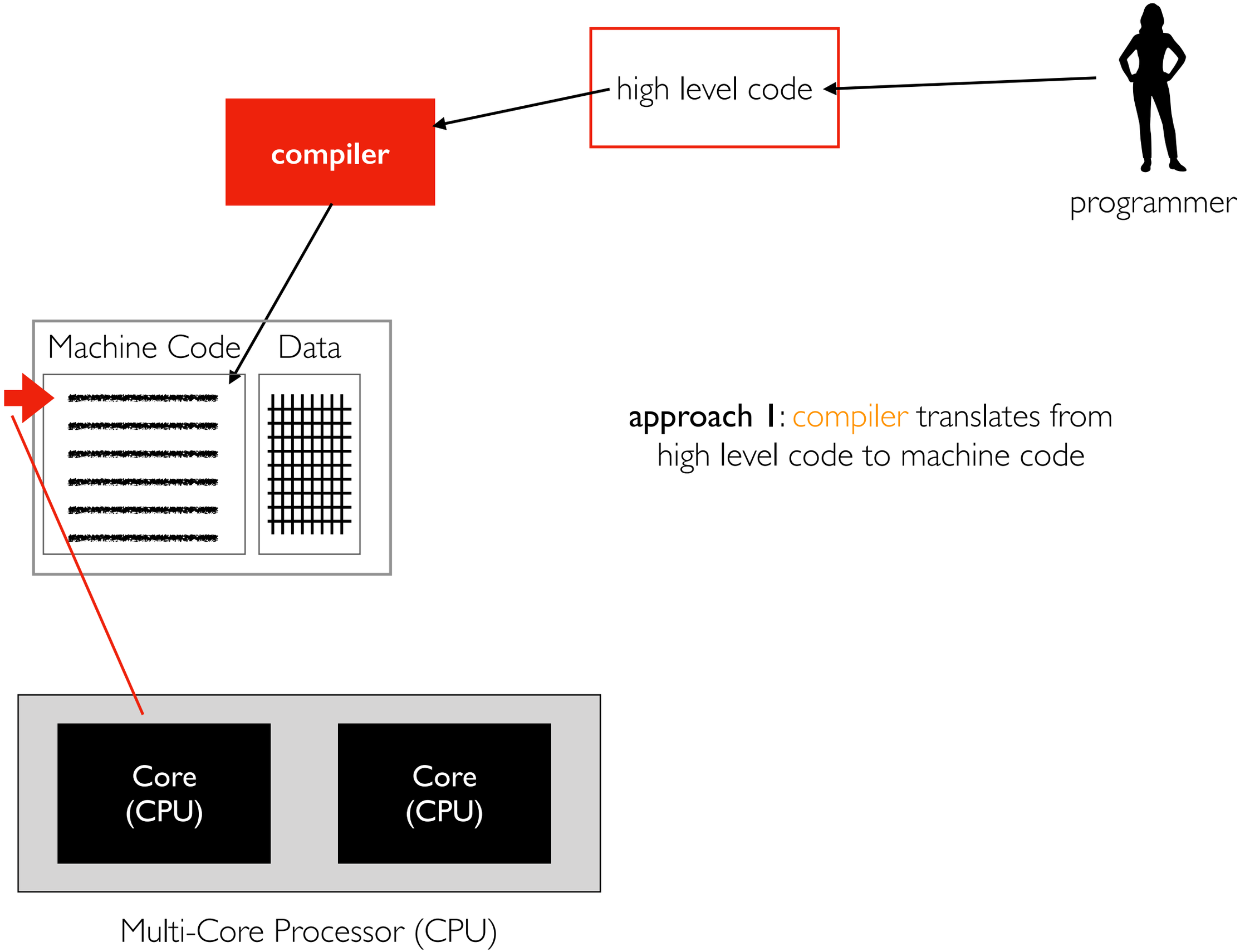
one operand instructions

```
incl dst       dst = dst + 1
decl dst       dst = dst - 1
negl dst       dst = -dst
notl dst       dst = ~dst
```

arithmetic ops set CCs implicitly

```
cf=1 if carry out from msb
zf=1 if dst==0,
sf=1 if dst < 0 (signed)
of=1 if two's complement
     (signed) under/overflow
```

how do we bridge the gap between "high level" code (C++/Python/Java/etc) and machine code?



approach 1: compiler translates from high level code to machine code

high level code

programmer

Machine Code Data

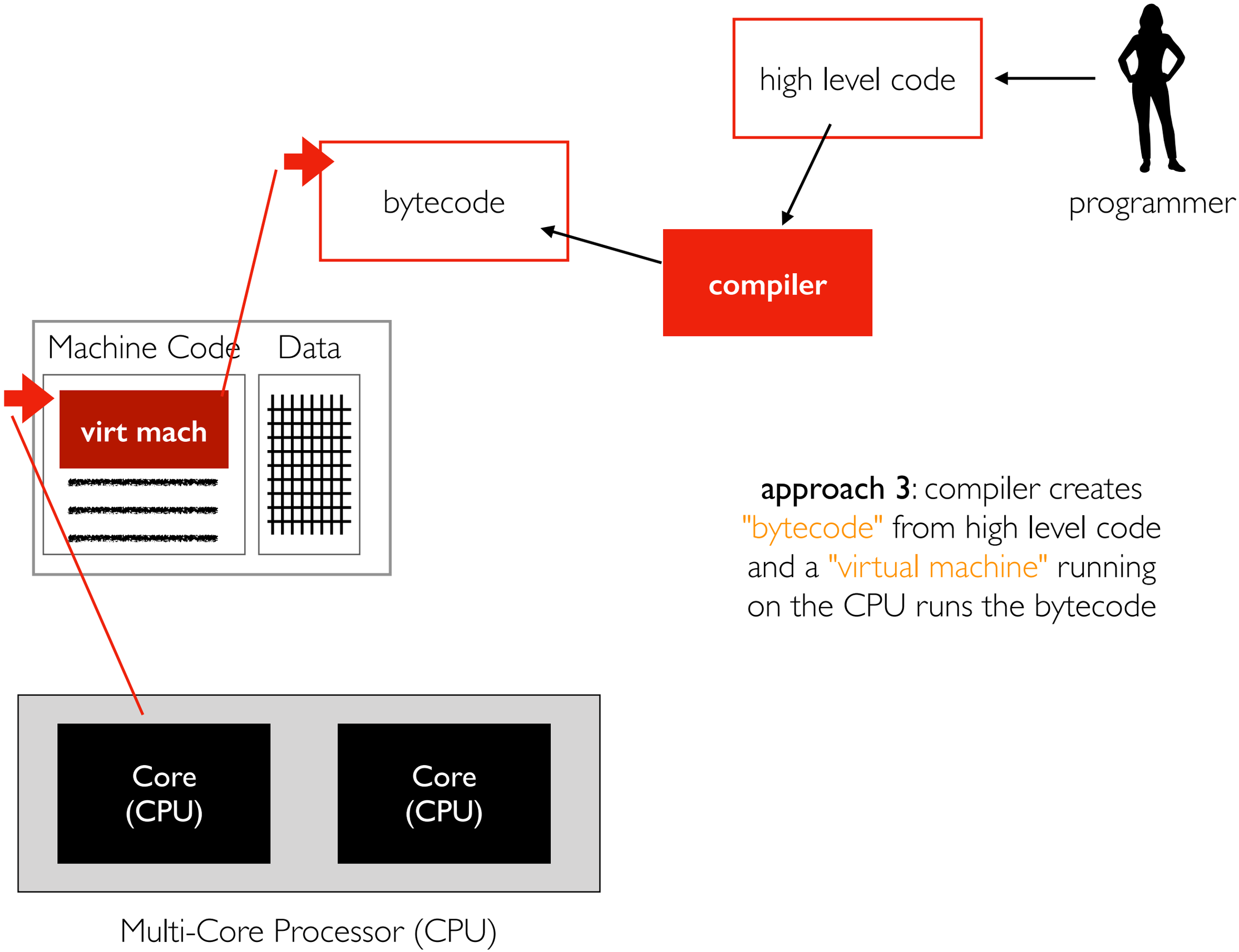
interpreter

Core (CPU)

Core (CPU)

Multi-Core Processor (CPU)

approach 2: CPU runs an interpeter program that loops over programmer's code and runs it



approach 3: compiler creates "bytecode" from high level code and a "virtual machine" running on the CPU runs the bytecode

when you run "python3 ..."
bytecode generation happens
automatically before Python
Virtual Machine runs it

Python Code

bytecode
(.pyc files)

compiler

Machine Code Data

PVM

JVM bytecode is "closer"
to machine code

Java Code

bytecode
(.class files)

Java compiler

javac mycode.java

java mycode

Machine Code Data

JVM

C/C++ Performance

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- however, cannot dynamically profile+optimize

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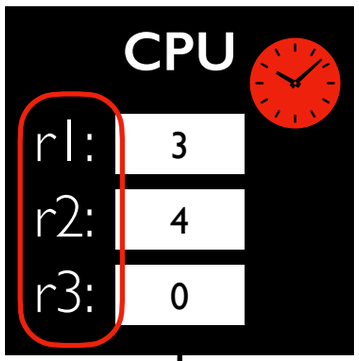
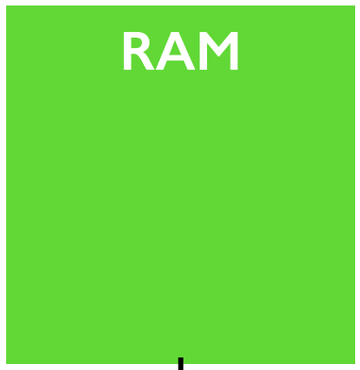
Background: CPU and RAM

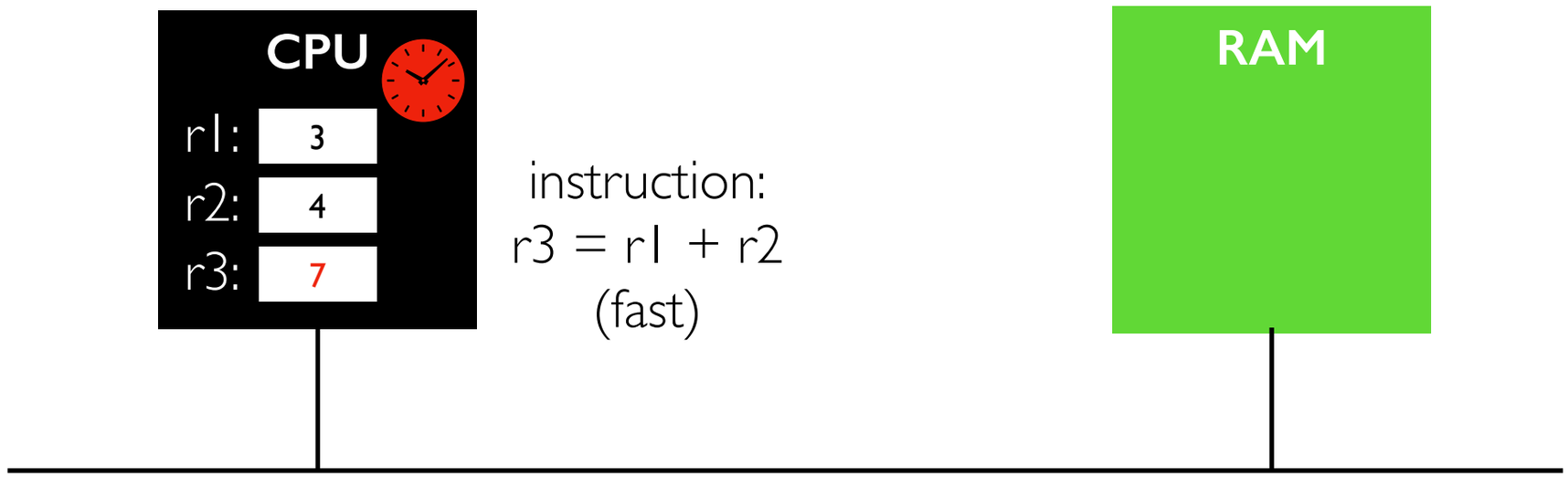
registers are like variables built into the CPU



CPU clock has billions of cycles per second



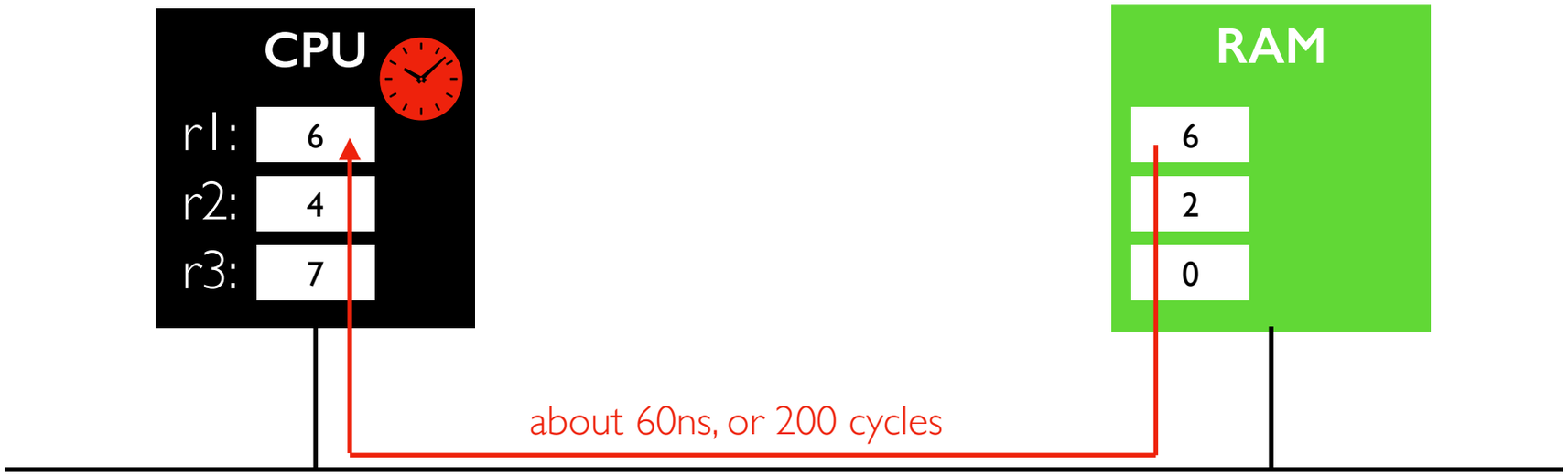
Background: CPU and RAM



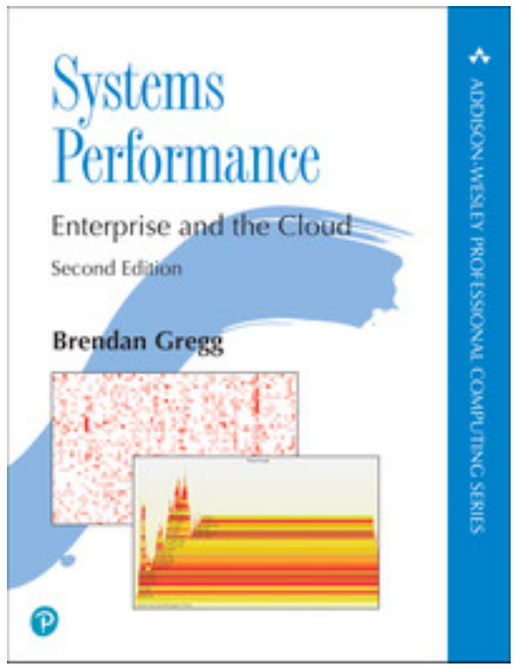
Load and Store

challenge: if we want to add some numbers stored in RAM, we need to **load** before adding and **store** after

Latency



very slow, but not long enough to switch to a different process...



source: visuals, estimates

Cache

What happens:

- the value needed (for example, a 4-byte integer) goes to the register
- a whole cacheline (often 64 bytes) containing the value goes to the cache
- future accesses to values in same cacheline will be relatively fast!

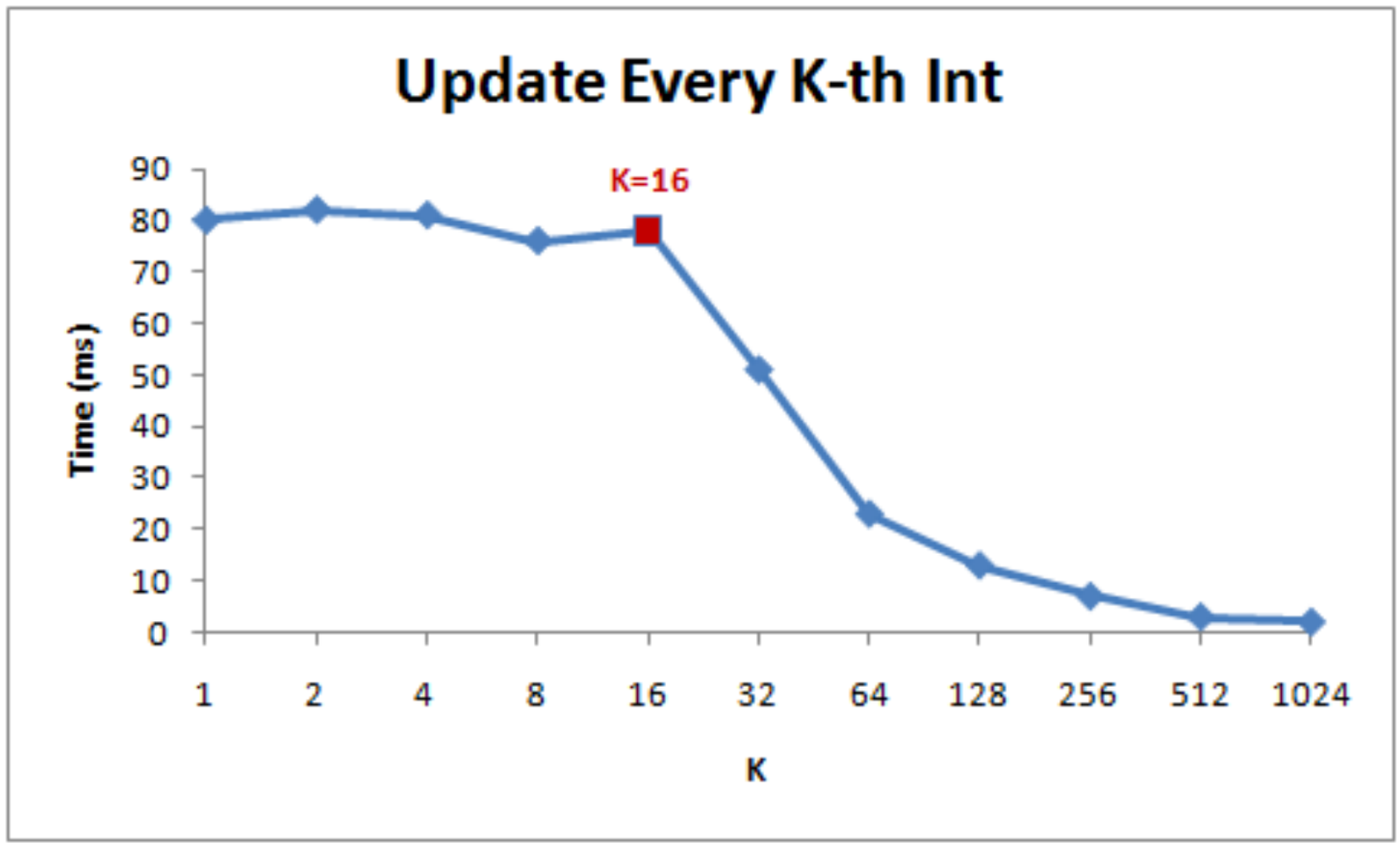
What matters for performance:

- how many cache misses there are (that is, how many times we need data that is not in the cache)
- how many values we access is less important

Example 1: Step and Multiply

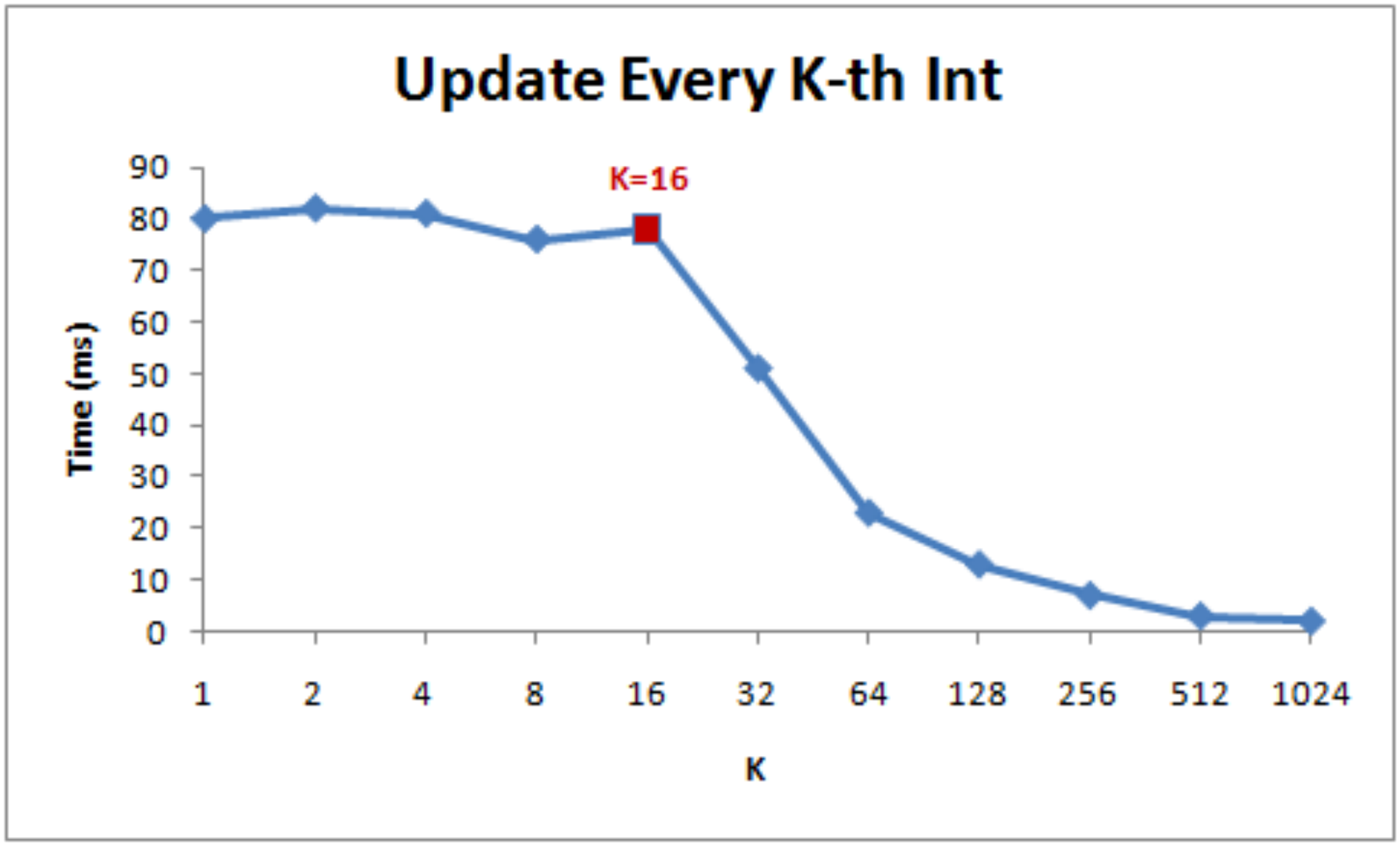
as K gets bigger, we do fewer multiplications. But does it matter?

```
for (int i = 0; i < arr.Length; i += K) arr[i] *= 3;
```



Gallery of Processor Cache Effects
http://igoro.com/archive/gallery-of-processor-cache-effects/

Example 1: Step and Multiply



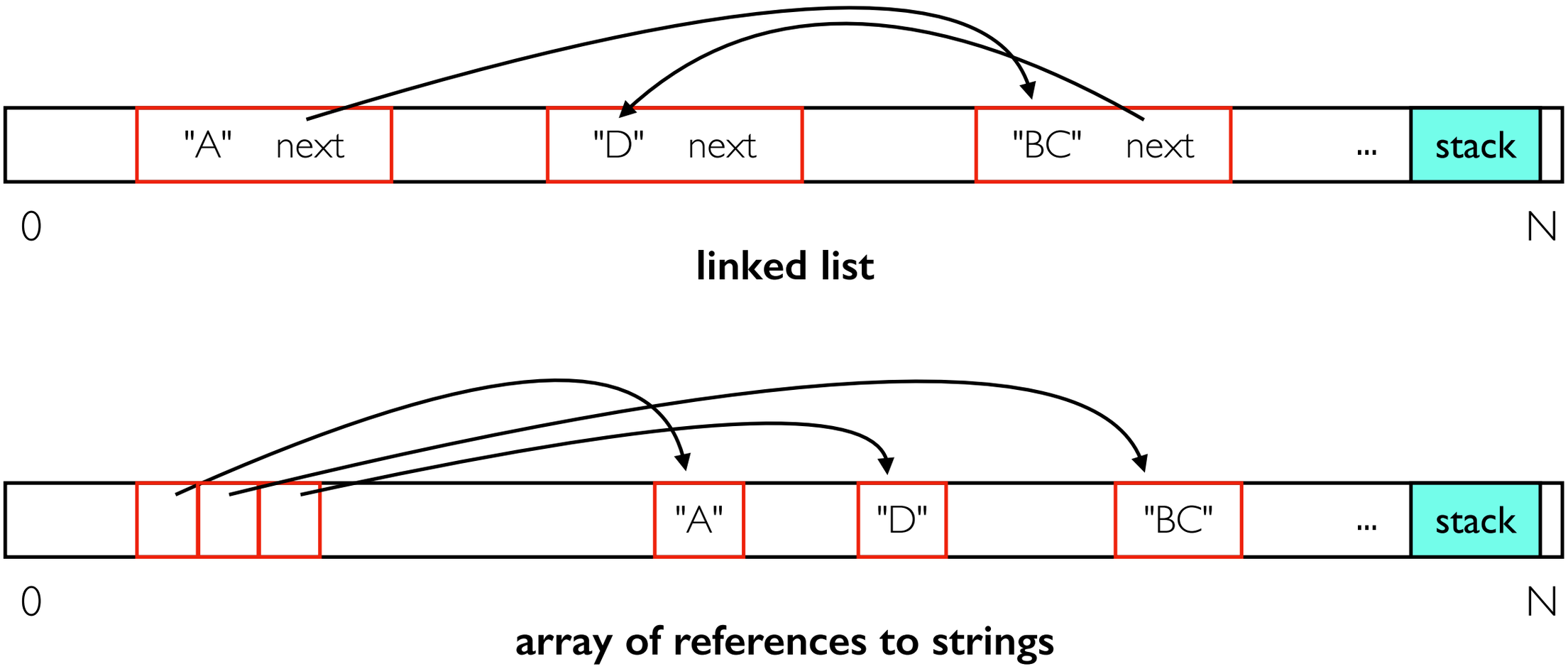
performance tip: think about how many cachelines you're touching, not just about how many values

k=1 loop: all the ints, all the cachelines

k=2 loop: half the ints, all the cachelines

Example 2: Series of Strings

which layout is most cache friendly?



linked list

array of references to strings

array of inline strings

C/C++ Performance

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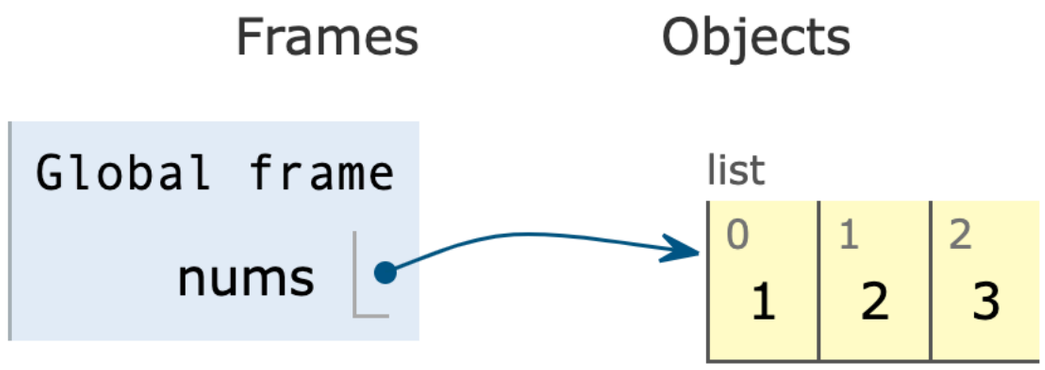
Background: Memory Management

https://pythontutor.com/

```
1  nums = [1,2,3]
2  items = nums
3  nums = [4,5,6]
4  items = None
```



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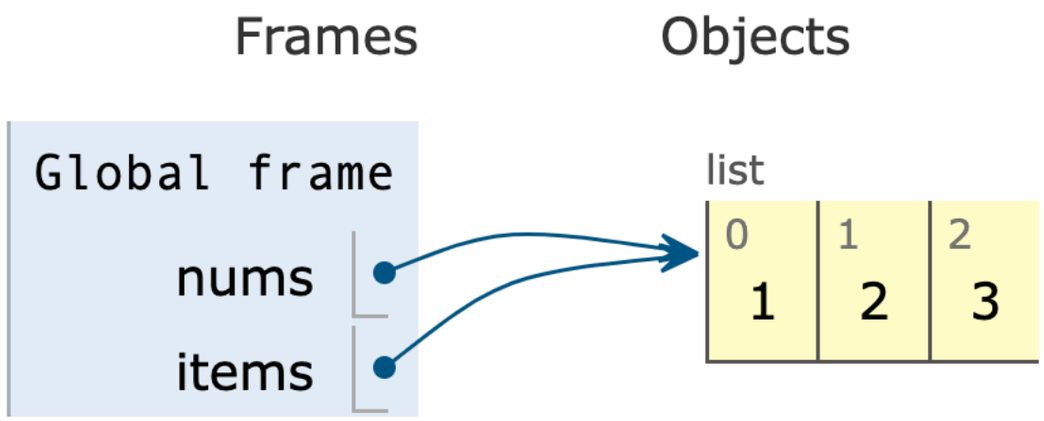

Background: Memory Management

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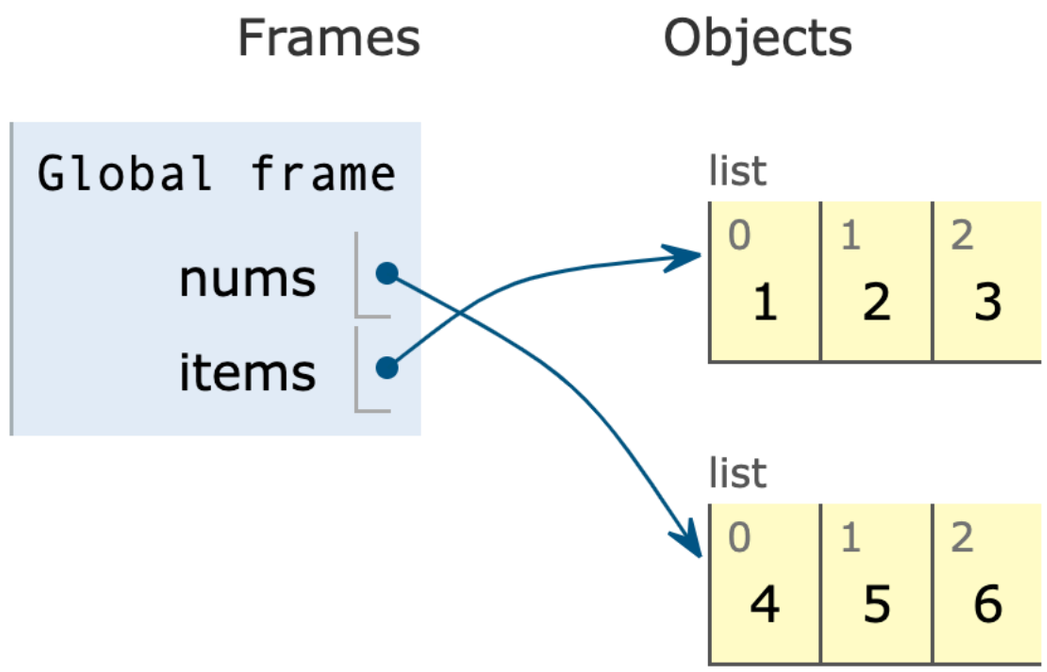
line that has just executed

next line to execute

line that has just executed



Background: Memory Management

- data that can no longer be accessed in any way is "garbage"
- we can release garbage to free up memory
- in simple cases, the garbage objects might be recognizable immediately
- in complicated cases (for example, circular references), a background garbage collection algorithm needs to run to identify garbage
- garbage collection is costly and generally involves pausing execution (perhaps for many seconds!)

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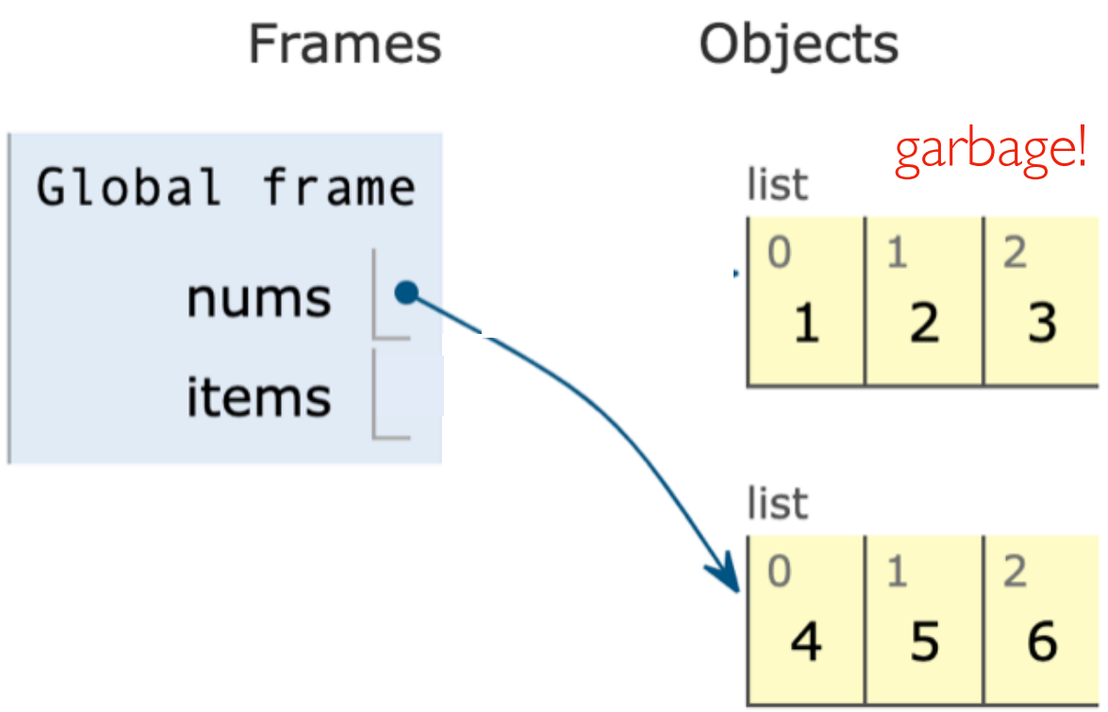

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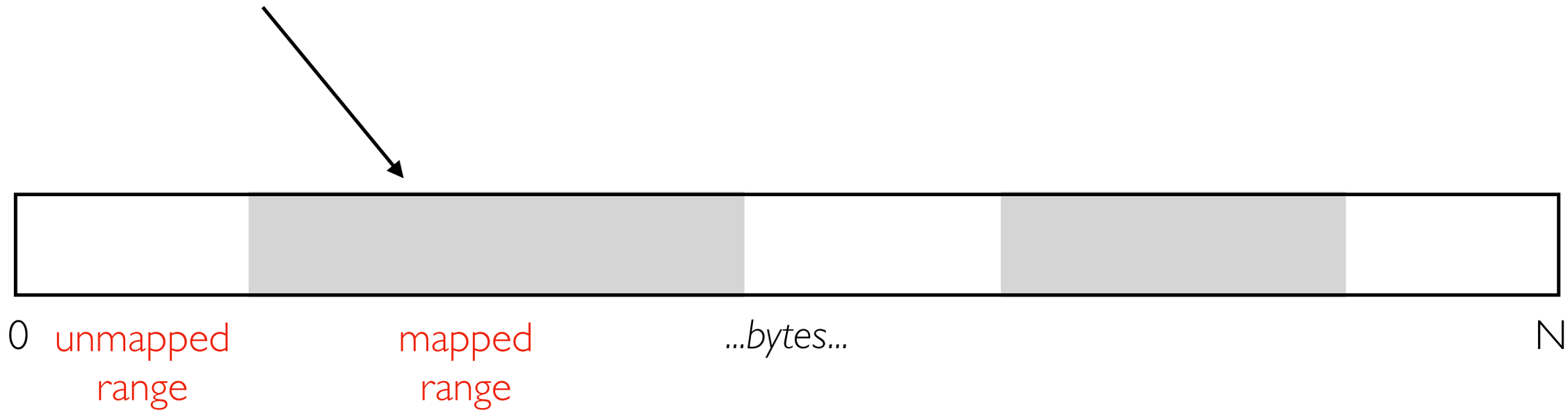
Background: Safety Checks

```
A = [5,6,7]
B = [8,9,1]
```

every process has an address space, which resembles a big array of bytes (indexes are called addresses). All the processes data lives somewhere in that address space.



A process is a running program. Each process has an "address space" that is basically a big array of bytes for all of its data. An "address" is an index into the array. Some ranges of addresses are "mapped" (valid) and others are unmapped.

Background: Safety Checks

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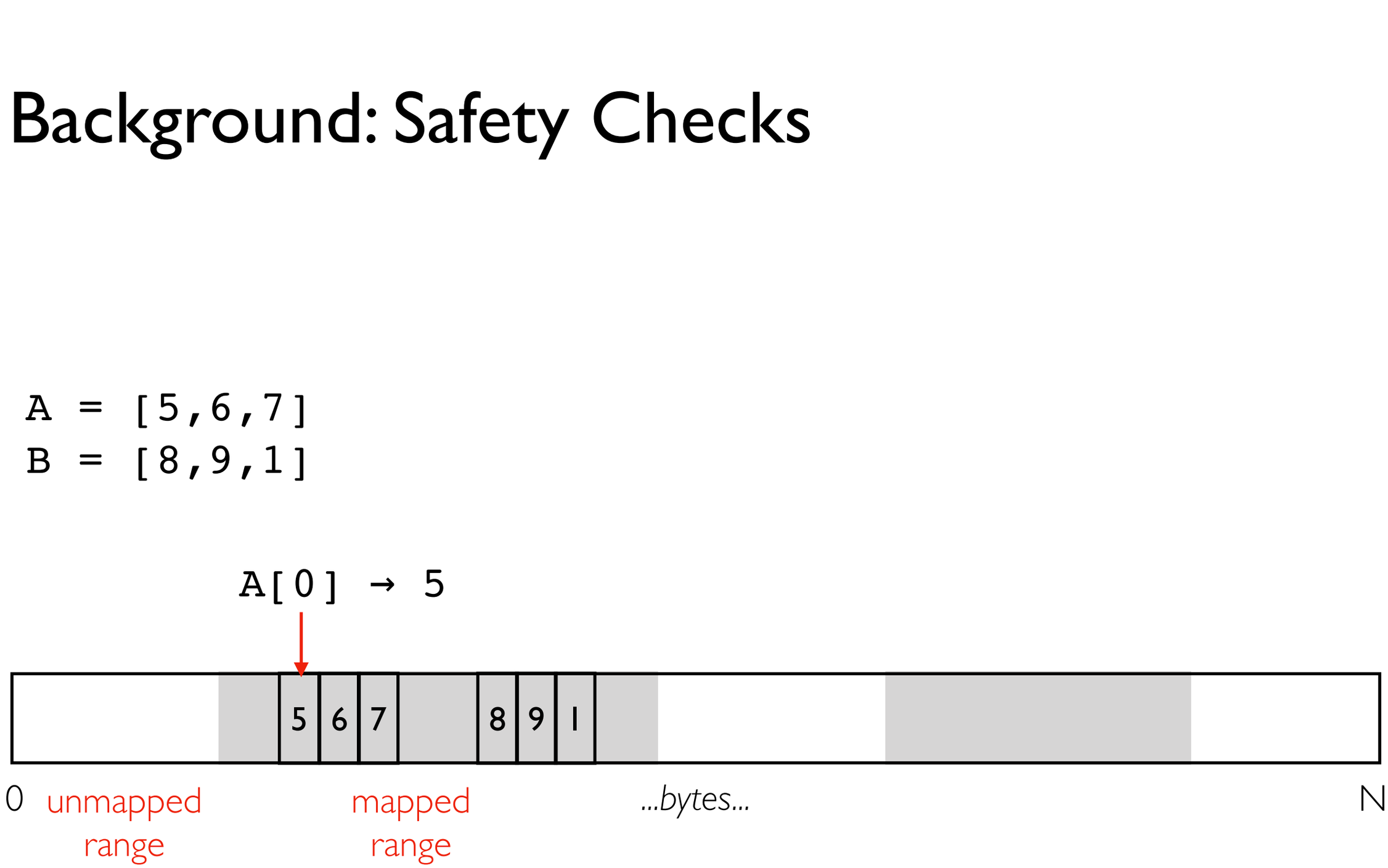

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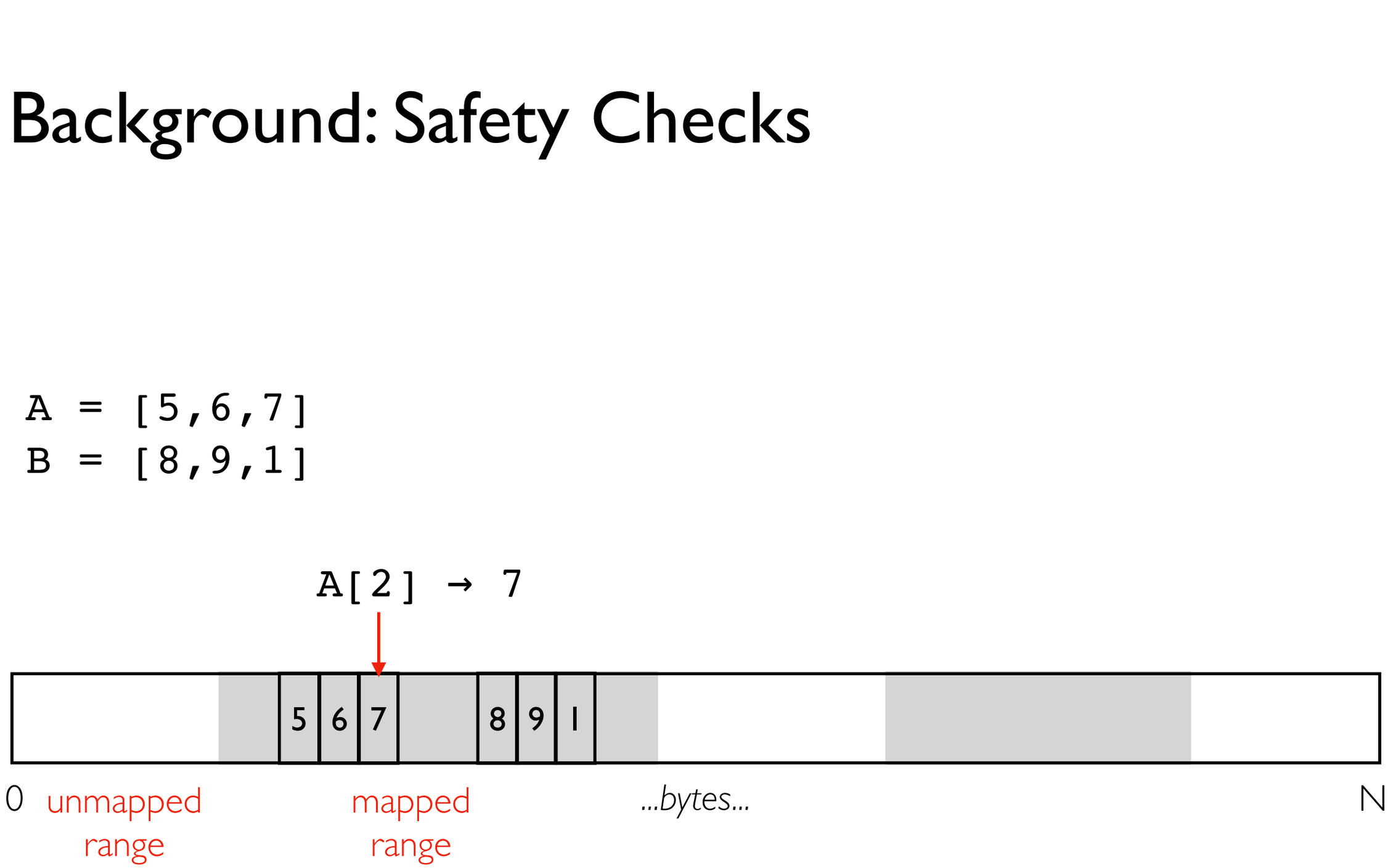
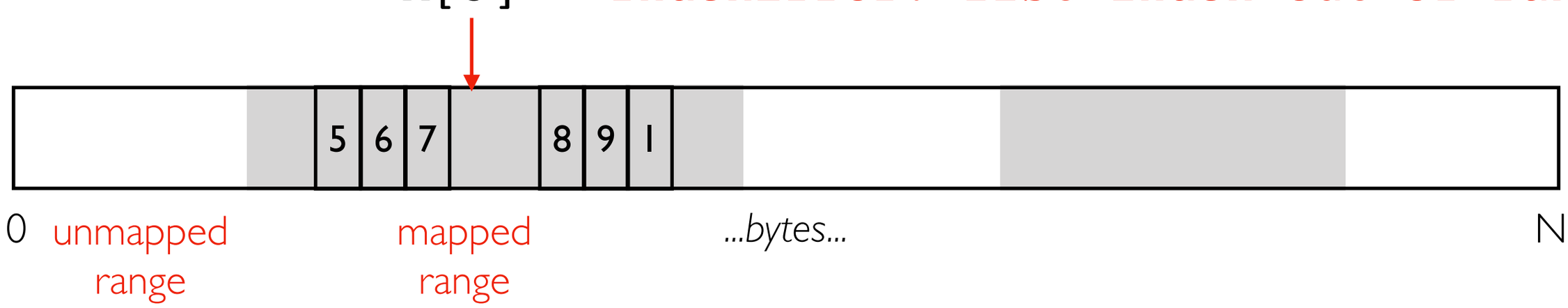


Background: Safety Checks

```
A = [5,6,7]
B = [8,9,1]
```

```
A[3] → IndexError: list index out of range
```



Many languages (Python, Java, etc) check bounds for you and raise an exception if you're outside. This checking has a performance cost, but is safer.

Bounds Checking

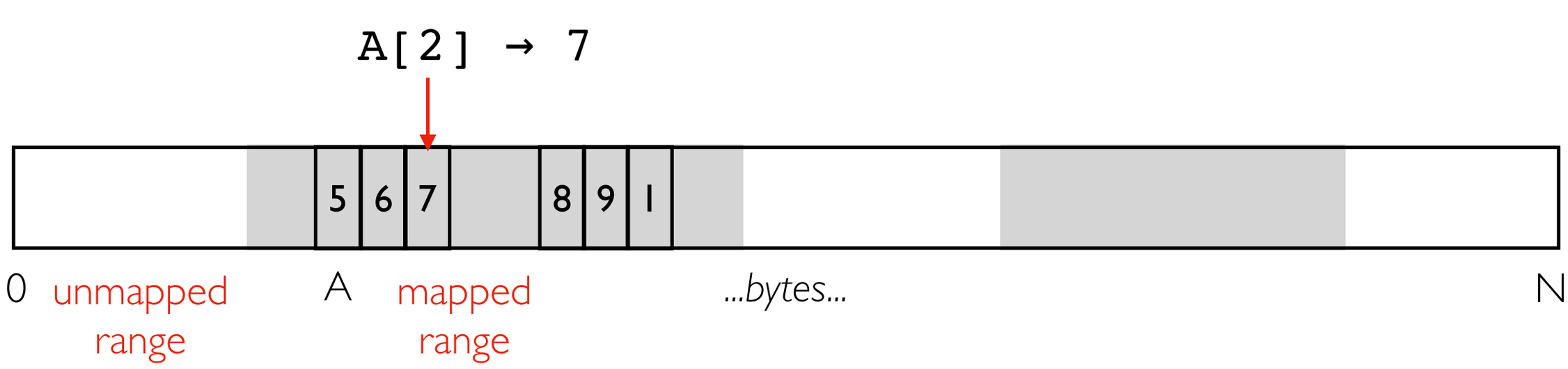
```
def print_at(items, idx):
    if 0 <= idx < len(items):
        print(items[idx])
    else:
        print("bad index")
```

Python checks that idx is in range, which is wasteful because your code already did that!

C/C++ Approach

Trust programmer to write code that checks bounds.

Generally don't spend time on double checking that!



When programmer makes a mistake, however, there are a variety of strange things that could happen...

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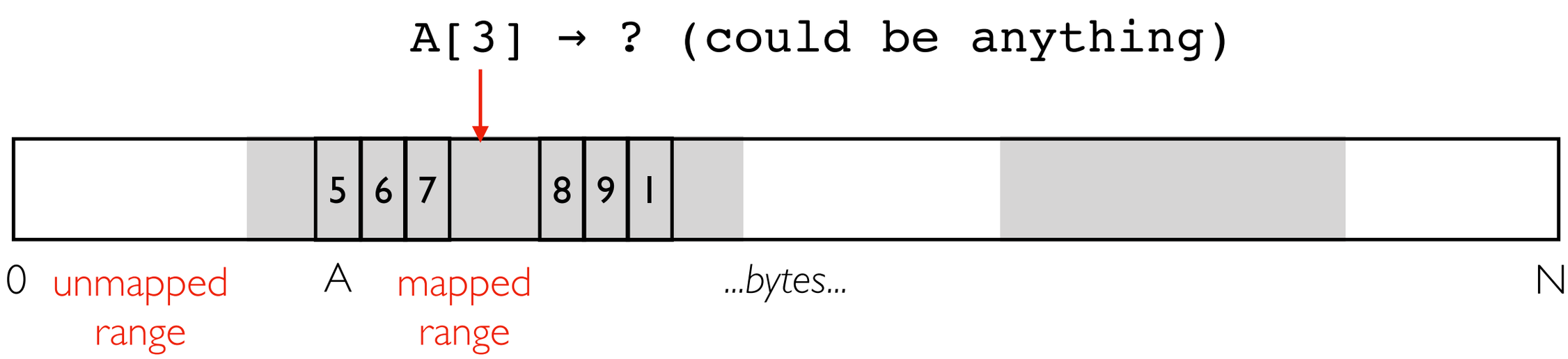

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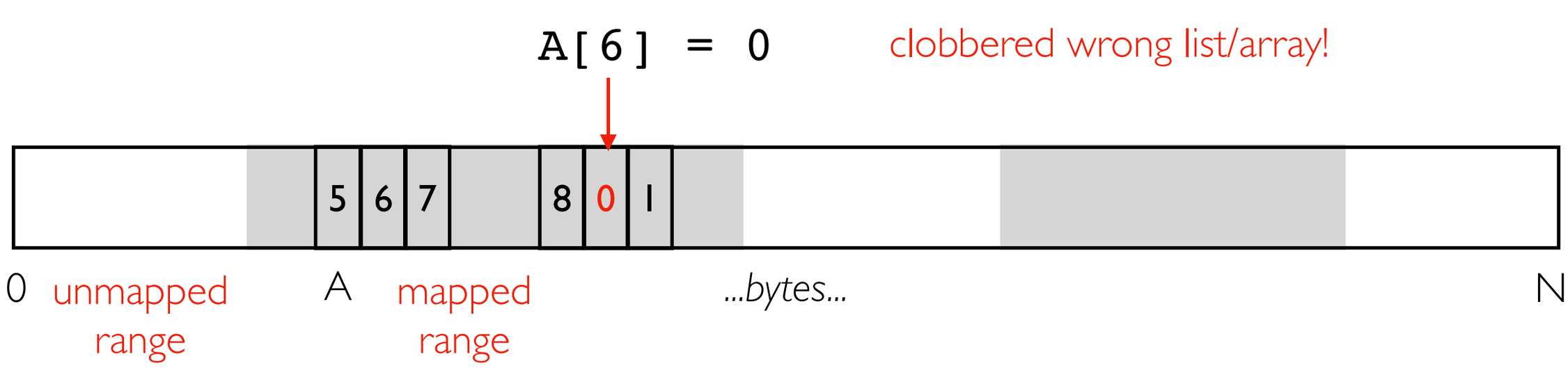

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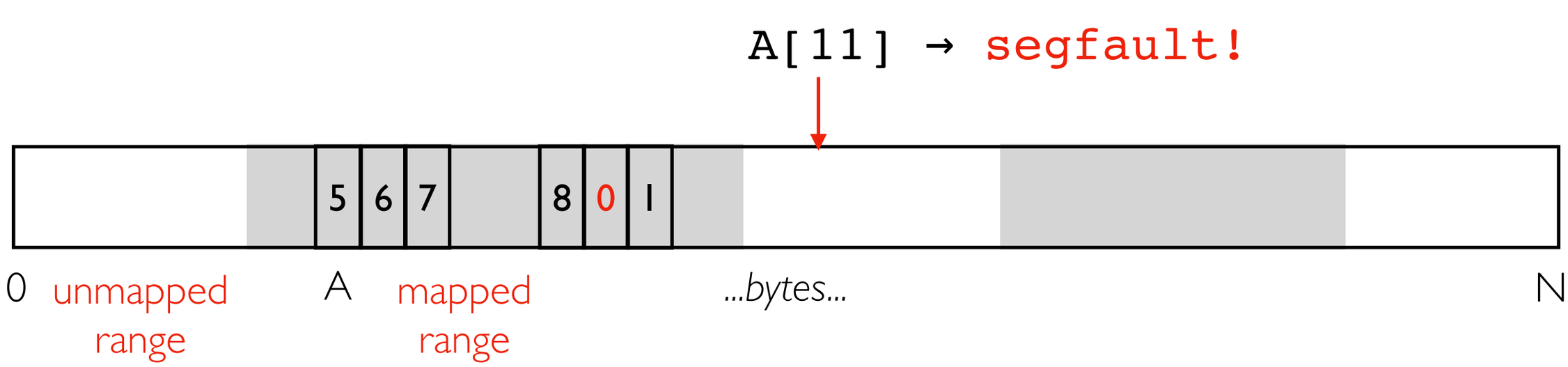

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Advantage 4: C/C++ doesn't spend much compute time to catch programming mistakes

- avoids duplicated checking effort
- runs a little faster

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- YOU (the p
- memory is
- no overhea

Advantage 4: C/C

- avoids dupli
- runs a little

Observation: almost all these performance features make programming more difficult and introduce new kinds for bugs (leaks, segfaults, etc).

Note: there are many tools for calling from one language to another (Python to C, Java to C++, etc).

Suggestion: if 80% of execution time is spent on 20% of your code, consider writing the critical 20% in a fast language (like C++) and the rest in an "easy" language (like Python)

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- Why C++ (over C): language features

Demos

A Few Language Features in C++ but not C

Function overloading

- multiple functions with the same name that accept different types

Type deduction

- use "auto" type (or other features) to let C++ decide what the time should be
- templating: don't need many different similar functions to handle different types

Alternatives to pointers

- references, smart pointers (for example, unique and shared)

OOP (Object Oriented Programming)

- classes, inheritance (multiple!), public/private/etc.

Resource management with RAII (Resource Acquisition is Initialization)

- use destructors to make sure resources are freed when necessary
- differentiate copy/move, manager ownership of objects over resources

Rich STL (Standard Library)

- containers, iterators, algorithms

Functional programming

- anonymous lambda functions
- many standard library functions that take function references

Outline

Welcome

Logistics

Background and Motivation

- Why C/C++: performance
- Why C++ (over C): language features

Demos