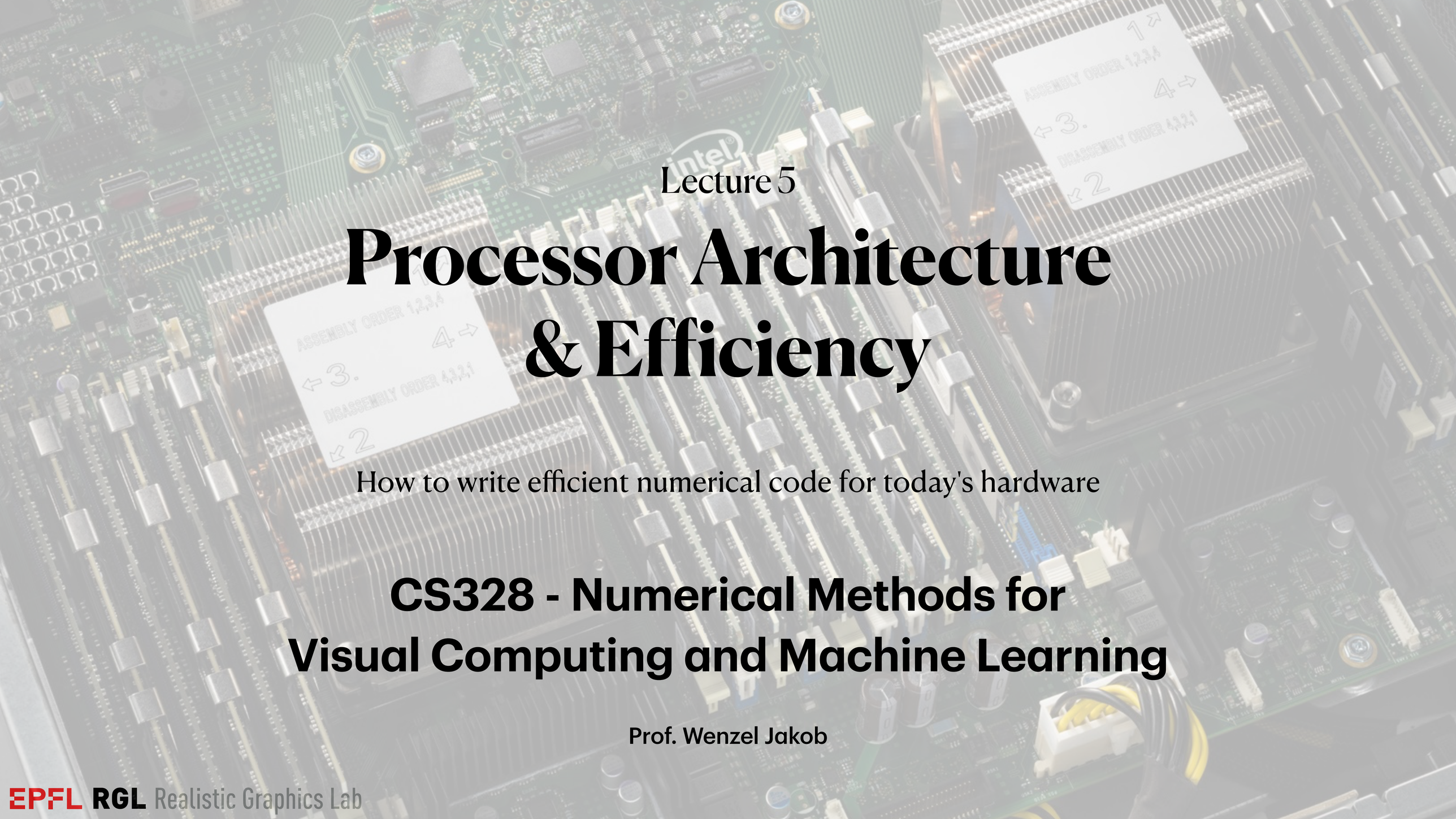


Lecture 5

# Processor Architecture & Efficiency

How to write efficient numerical code for today's hardware

## CS328 - Numerical Methods for Visual Computing and Machine Learning

Prof. Wenzel Jakob

EPFL RGL Realistic Graphics Lab

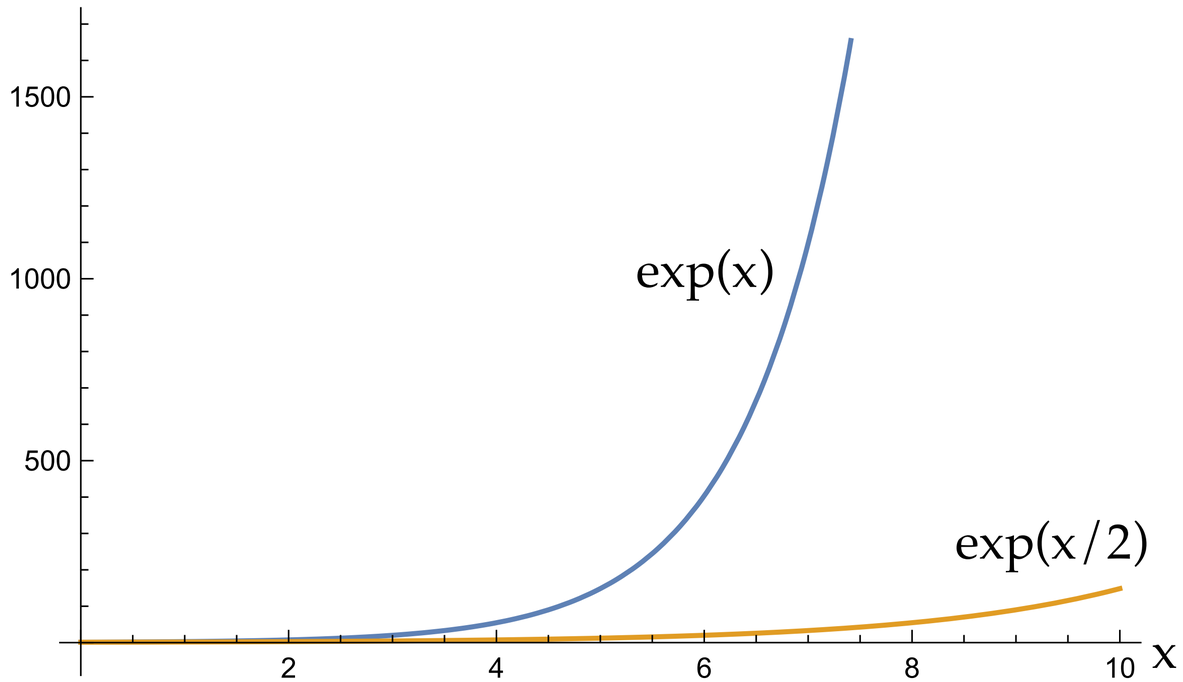
# Course evaluations

**Don't forget to review your courses (including CS328) until October 22**

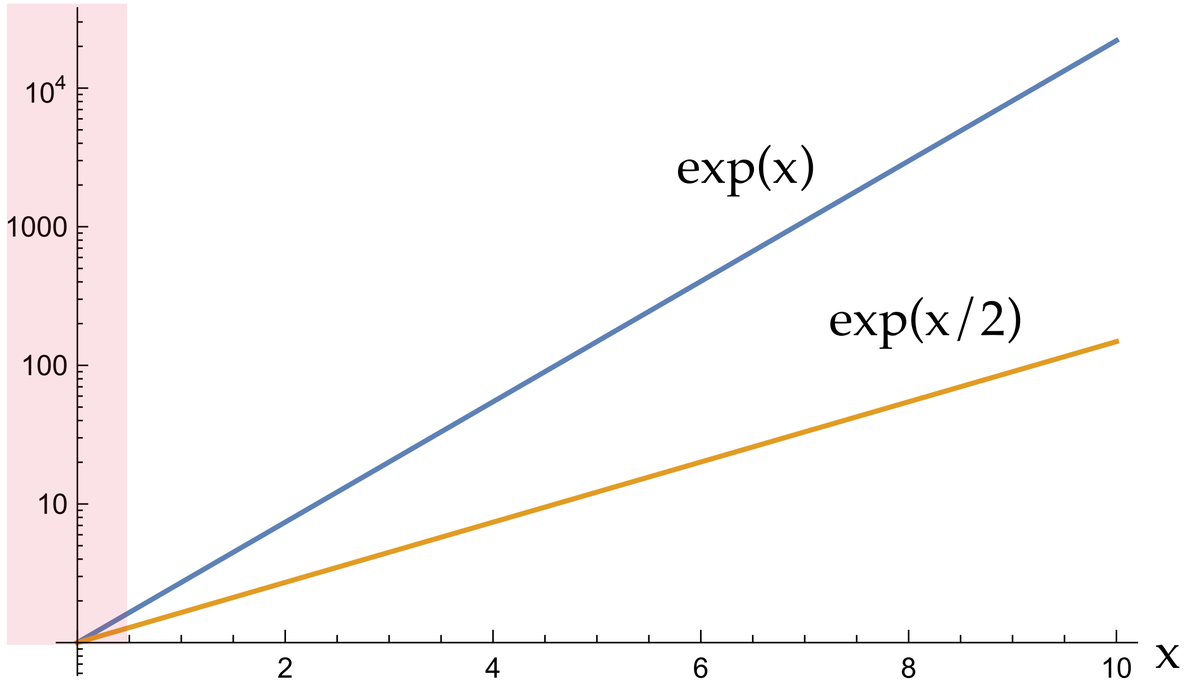
- What you write in there **really matters.**
  - I read it. The TAs read it.
  - The IC sections read it.
  - If it's very bad (or *very good*) it, the IC sections follows up with course instructors.
  - Curious about your thoughts!

**MidJourney**: a person putting a piece of paper into a ballot box, on white background.

# A Semi-Log Plot: What is it? How to read it?




Linear plot




Semi-log plot

# Motivation: A Story of Nonlinear Growth

- **2020 ACM Turing Award**
  "Nobel Prize" for Computer Science

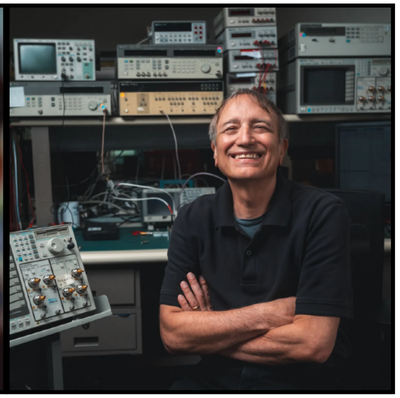
- 1979: Catmull joined Lucasfilm to create a *computer division* and make a digital movie.

- A **preposterous** idea: would have needed the power of 1000 CRAY-1 supercomputers (10 million US $ for just one)...
  .. but only had a budget of 1M $.

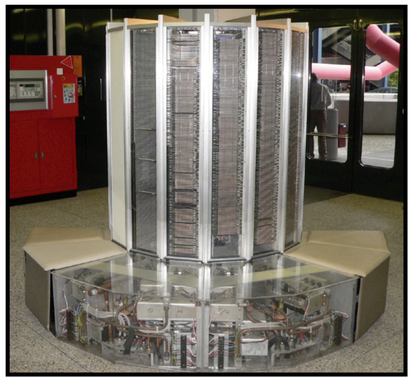
- Catmull: "*Based on where we were on the exponential curve for computing speed, it would take another 14-15 years. Our time and resources were better spent on the many problems we could see here and now. Coincidentally, when we released "Toy Story" about 15 years later, we were very close to our estimate of the computing power required.*"

**Image Credits:** Deborah Coleman / Pixar; Andrew Brodhead / Stanford University

Ed Catmull

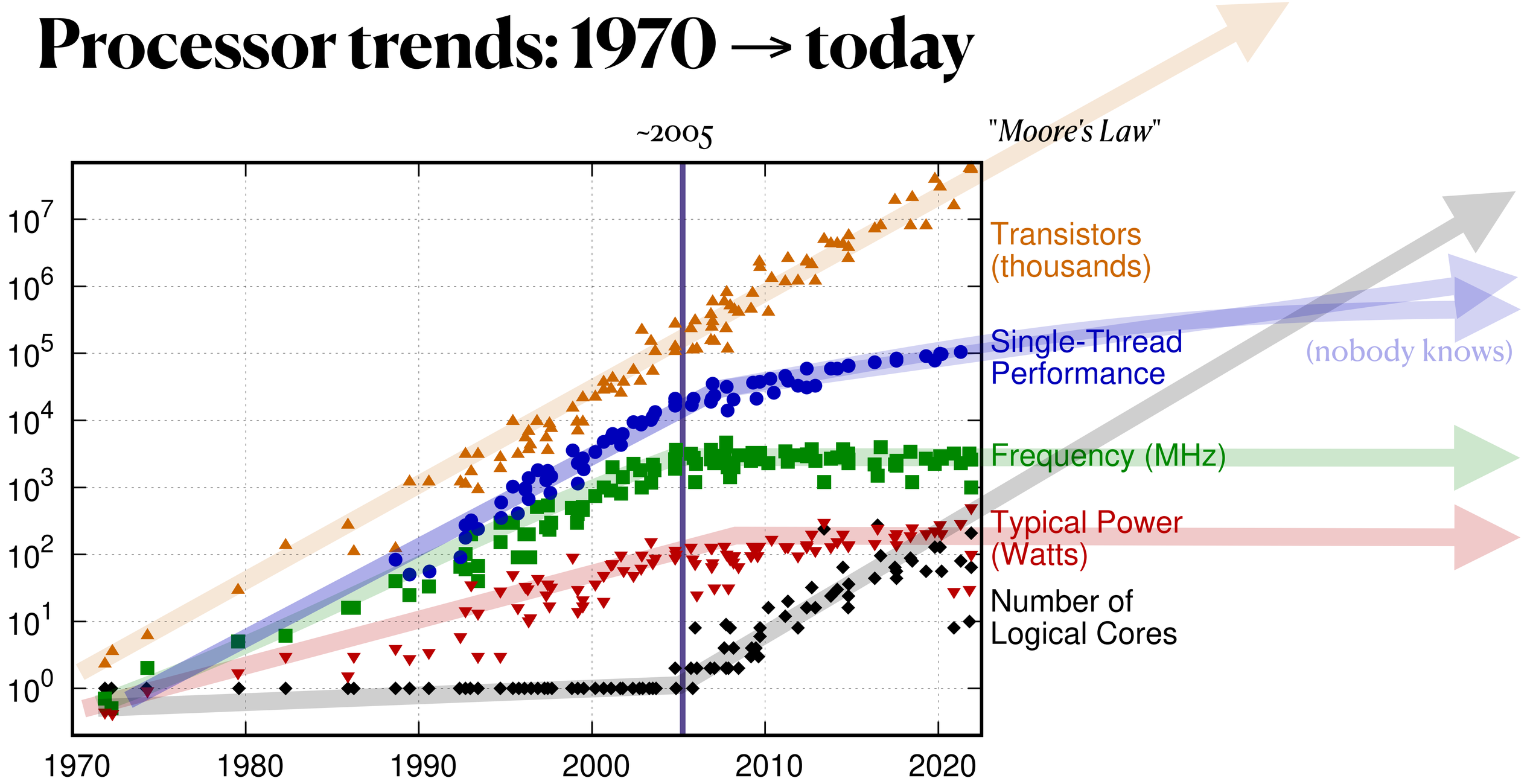


Pat Hanrahan



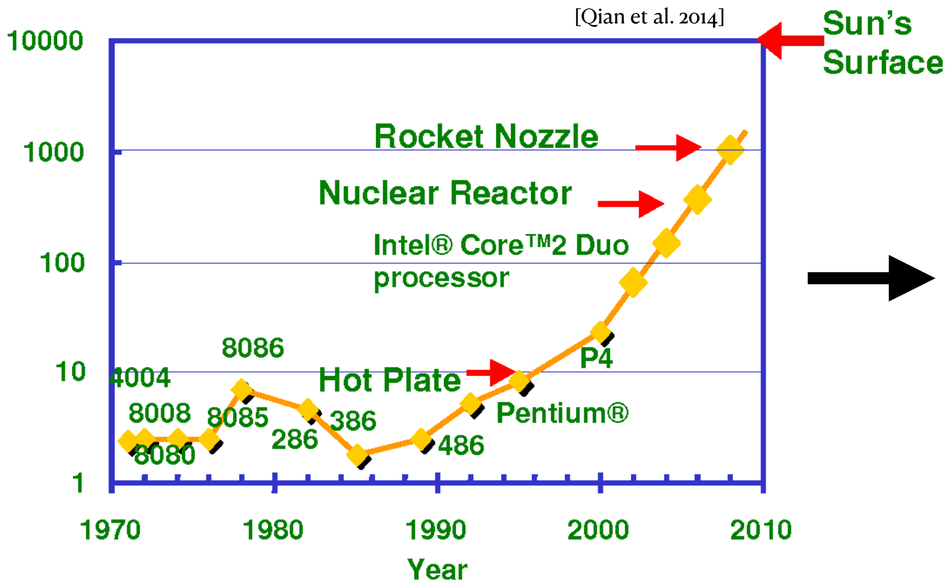
CRAY-1
Supercomputer

# Processor trends: 1970 → today




[Source: https://github.com/karlrupp/microprocessor-trend-data]

# But what does it *mean*?



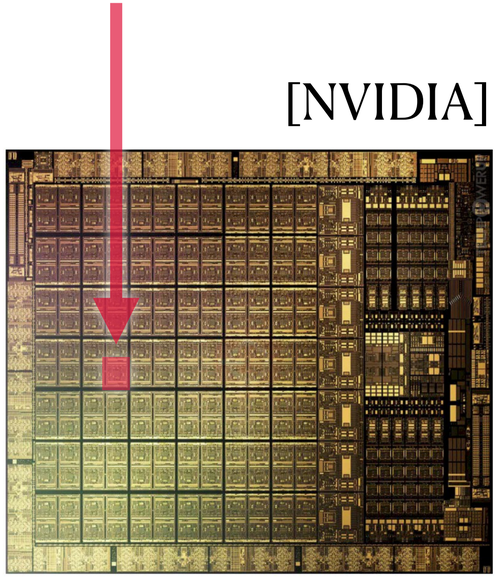

We hit a power wall at ~100 W/cm²

⇒ Frequency fixed because raising it increases power usage & temperature.

**MidJourney**: *a sad computer*

Our processors aren't getting much faster anymore.

[NVIDIA]



The only thing we can do is to have *more processors*.

(Multi-core CPUs, GPUs)

# Why this history lesson?

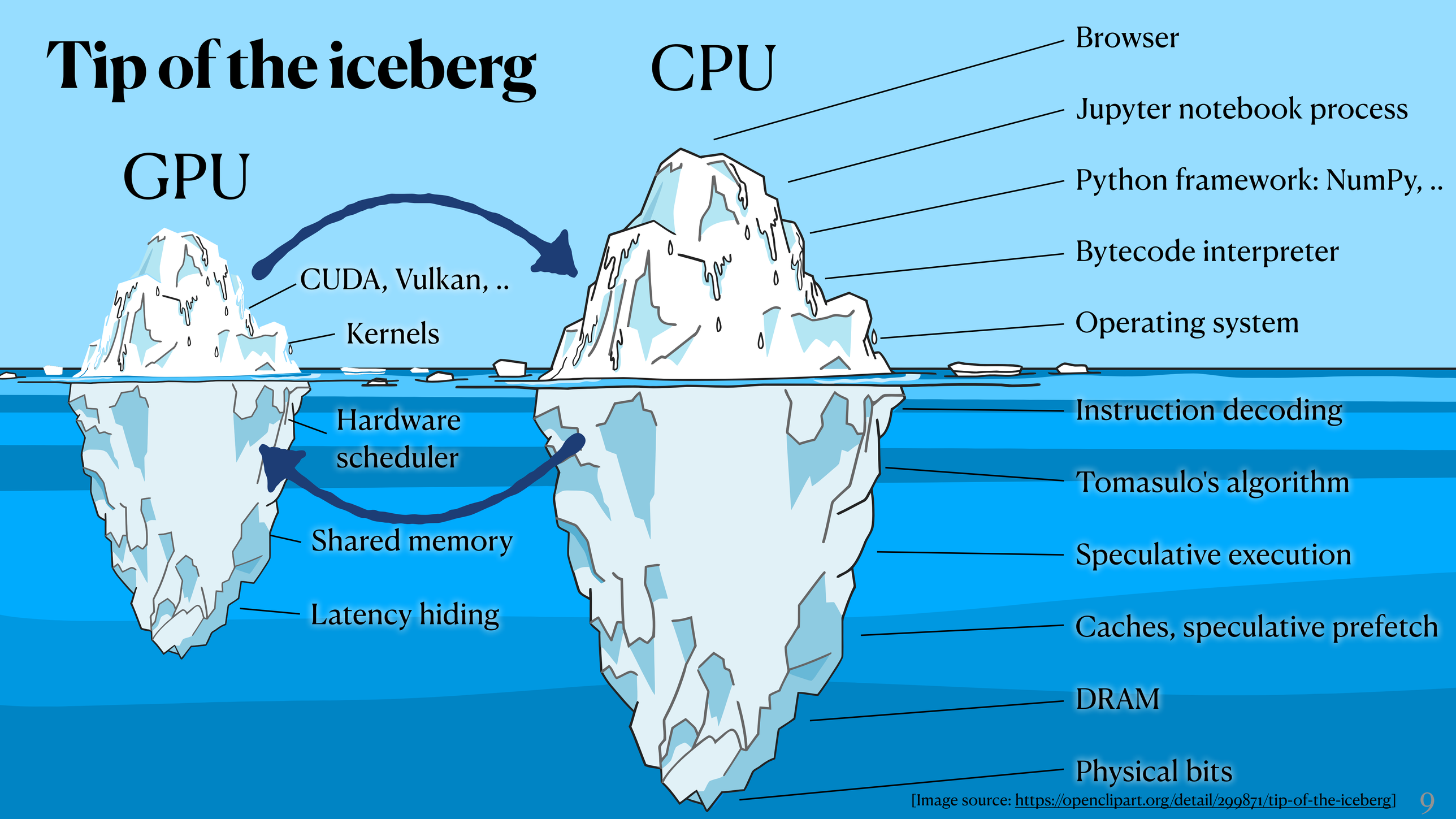
- Only way to get good performance nowadays is to anticipate how an algorithm will run on a particular piece of hardware and then *design for it*.
- Sometimes that means using a good implementation of a common building block (e.g. matrix factorization built by Intel/NVIDIA/..). When your needs are more special, you will likely have to make it yourself.
- Can easily get order-of-magnitude speedups. That might mean the difference between:
  - Your project is a **smashing success**.
  - **Nobody cares** about what you do.
- Important even if you don't care about "low level stuff". (@SysCom students 😉)

# Today's lecture

- This lecture is a **deep dive** into the performance of a simple operation.
- If you haven't seen such things before and it is all a little overwhelming:
  - *Don't be scared.*
    - You don't have to learn C++ or assembly code for the CS328 final exam.
  - *Don't look away.*
    - Still, you should know that these things exist, and how they *~roughly~* work.

MidJourney: *a deep sea diver in the ocean*

# Tip of the iceberg




[Image source: https://openclipart.org/detail/299871/tip-of-the-iceberg]

# Model problem

**A simple enough operation, but one that isn't "natively" supported by NumPy**

- `psum(x)`: sum the positive elements of the input vector "x"

If you want to follow along:
https://github.com/wjakob/psum

This repository is *not* relevant for homework or the final exam.

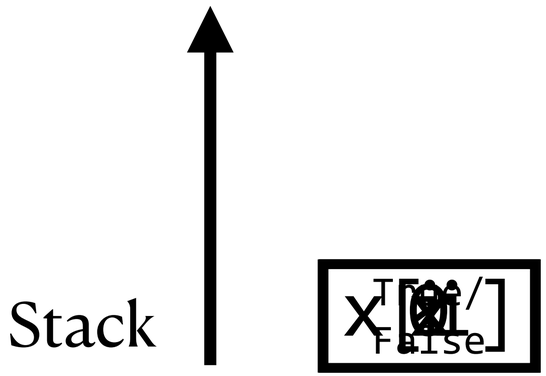
I uploaded it for those interested in the nitty-gritty details.

# Demo time

# Python bytecode

```
def psum(x):
    r = 0
    for i in range(len(x)):
        if x[i] > 0:
            r += x[i]
    return r

# Bytecode disassembler
import dis
dis.dis(psum)
```

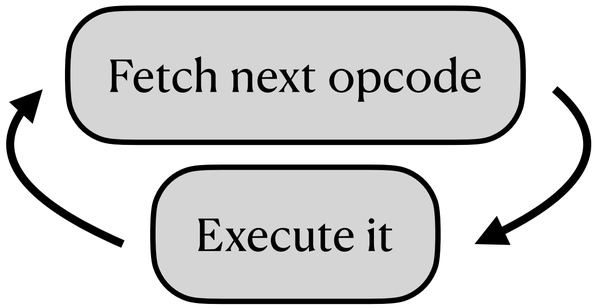
```
  0 LOAD_CONST               1 (0)
  2 STORE_FAST               1 (r)

  4 SETUP_LOOP              44 (to 50)
  6 LOAD_GLOBAL              0 (range)
  8 LOAD_GLOBAL              1 (len)
 10 LOAD_FAST                0 (x)
 12 CALL_FUNCTION            1
 14 CALL_FUNCTION            1
 16 GET_ITER
>>   18 FOR_ITER                28 (to 48)
 20 STORE_FAST               2 (i)

 22 LOAD_FAST                0 (x)
 24 LOAD_FAST                2 (i)
 26 BINARY_SUBSCR
 28 LOAD_CONST               1 (0)
 30 COMPARE_OP               4 (>)
 32 POP_JUMP_IF_FALSE       18

 34 LOAD_FAST                1 (r)
 36 LOAD_FAST                0 (x)
 38 LOAD_FAST                2 (i)
 40 BINARY_SUBSCR
 42 INPLACE_ADD
 44 STORE_FAST               1 (r)
 46 JUMP_ABSOLUTE           18
>>   48 POP_BLOCK

>>   50 LOAD_FAST                1 (r)
 52 RETURN_VALUE
```



# Dissecting the Python interpreter

## Let's follow the path of a single instruction

```
switch (opcode) { // ceval.c:1848
    case ...:
    case ...:
    case ...:
    case ...:
    case ...:
    case ...:
    case ...:
}
```




Big loop that fetches the next *opcode* and jumps to one of ~130 different code blocks.

```
case TARGET(COMPARE_OP): { ceval.c:3629
    assert(oparg <= Py_GE);
    PyObject *right = POP();
    PyObject *left = TOP();
    PyObject *res = PyObject_RichCompare(
            left, right, oparg);
    SET_TOP(res);
    Py_DECREF(left);
    Py_DECREF(right);
    if (res == NULL)
        goto error;
    PREDICT(POP_JUMP_IF_FALSE);
    PREDICT(POP_JUMP_IF_TRUE);
    DISPATCH();
}
```

Pops two operand from stack, pushes result back.
Reference counting, error management.
`left`, `right` could be anything at this point.

# Dissecting the Python interpreter

## Let's follow the path of a single instruction

```
case TARGET(COMPARE_OP): { ceval.c:3629
    assert(oparg <= Py_GE);
    PyObject *right = POP();
    PyObject *left = TOP();
    PyObject *res = PyObject_RichCompare(
           left, right, oparg);
    SET_TOP(res);
    Py_DECREF(left);
    Py_DECREF(right);
    if (res == NULL)
        goto error;
    PREDICT(POP_JUMP_IF_FALSE);
    PREDICT(POP_JUMP_IF_TRUE);
    DISPATCH();
}
```

Pops two operand from stack, pushes result back.

Reference counting, error management.

`left`, `right` could be anything at this point.

```
PyObject * PyObject_RichCompare( // object.c:729
    PyObject *v, PyObject *w, int op) {
    PyThreadState *tstate = _PyThreadState_GET();

    assert(Py_LT <= op && op <= Py_GE);
    if (v == NULL || w == NULL) {
        if (!_PyErr_Occurred(tstate)) {
            PyErr_BadInternalCall();
        }
        return NULL;
    }
    if (_Py_EnterRecursiveCall(tstate,
        " in comparison")) {
        return NULL;
    }
    PyObject *res = do_richcompare(
        tstate, v, w, op);
    _Py_LeaveRecursiveCall(tstate);
    return res;
}
```

Makes sure that there is no stack overflow.

# Dissecting the Python interpreter

## Let's follow the path of a single instruction

```
PyObject * PyObject_RichCompare( // object.c:729
    PyObject *v, PyObject *w, int op) {
    PyThreadState *tstate = _PyThreadState_GET();

    assert(Py_LT <= op && op <= Py_GE);
    if (v == NULL || w == NULL) {
        if (!_PyErr_Occurred(tstate)) {
            PyErr_BadInternalCall();
        }
        return NULL;
    }
    if (_Py_EnterRecursiveCall(tstate,
        " in comparison")) {
        return NULL;
    }
    PyObject *res = do_richcompare(
        tstate, v, w, op);
    _Py_LeaveRecursiveCall(tstate);
    return res;
}
```

Makes sure that there is no stack overflow.

```
// object.c:676
static PyObject *
do_richcompare(PyThreadState *tstate,
      PyObject *v, PyObject *w, int op)
{
    richcmpfunc f;
    PyObject *res;
    int checked_reverse_op = 0;

    if (!Py_IS_TYPE(v, Py_TYPE(w)) &&
        PyType_IsSubtype(Py_TYPE(w), Py_TYPE(v)) &&
        (f = Py_TYPE(w)->tp_richcompare) != NULL) {
        checked_reverse_op = 1;
        res = (*f)(w, v, _Py_SwappedOp[op]);
        if (res != Py_NotImplemented)
            return res;
        Py_DECREF(res);
    }
    if ((f = Py_TYPE(v)->tp_richcompare) != NULL) {
        res = (*f)(v, w, op);
        if (res != Py_NotImplemented)
            return res;
        Py_DECREF(res);
    }
    if (!checked_reverse_op &&
        (f = Py_TYPE(w)->tp_richcompare) != NULL) {
        res = (*f)(w, v, _Py_SwappedOp[op]);
        if (res != Py_NotImplemented)
```

# Dissecting the Python interpreter

## Let's follow the path of a single instruction

```
    res = (*f)(v, w, op);
    if (res != Py_NotImplemented)
        return res;
    Py_DECREF(res);
}
if (!checked_reverse_op &&
    (f = Py_TYPE(w)->tp_richcompare) != NULL) {
    res = (*f)(w, v, _Py_SwappedOp[op]);
    if (res != Py_NotImplemented)
        return res;
    Py_DECREF(res);
}
/* If neither object implements it, provide a sensible default
   for == and !=, but raise an exception for ordering. */
switch (op) {
case Py_EQ:
    res = (v == w) ? Py_True : Py_False;
    break;
case Py_NE:
    res = (v != w) ? Py_True : Py_False;
    break;
default:
    _PyErr_Format(tstate, PyExc_TypeError,
                  "'%s' not supported between "
                  "instances of '%.100s' and '%.100s'",
                  opstrings[op],
                  Py_TYPE(v)->tp_name,
                  Py_TYPE(w)->tp_name);
```

floatobject.c:362

```
/* Comparison is pretty much a nightmare.  When comparing
 * we do it as straightforwardly (and long-windedly) as co
 * that, e.g., Python x == y delivers the same result as t
 * C x == y when x and/or y is a NaN.
 * When mixing float with an integer type, there's no good
 * Converting the double to an integer obviously doesn't w
 * may lose info from fractional bits.  Converting the int
 * also has two failure modes:  (1) an int may trigger ove
 * large to fit in the dynamic range of a C double); (2) e
 * more bits than fit in a C double (e.g., on a 64-bit box
 * 63 bits of precision, but a C double probably has only
 * we can falsely claim equality when low-order integer bi
 * coercion to double.  So this part is painful too.
 */

static PyObject*
float_richcompare(PyObject *v, PyObject *w, int op)
{
    double i, j;
    int r = 0;

    assert(PyFloat_Check(v));
    i = PyFloat_AS_DOUBLE(v);

    /* Switch on the type of w.  Set i and j to doubles to
```

# Dissecting the Python interpreter

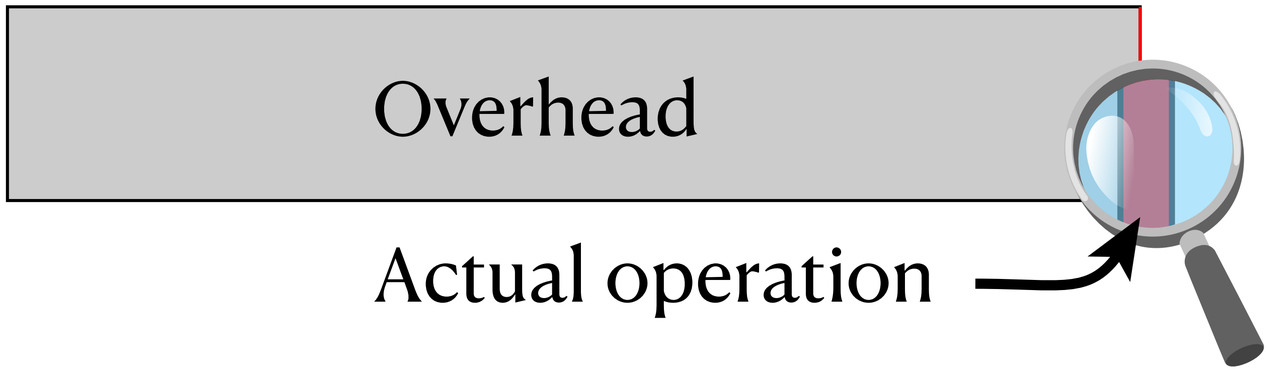
## Let's follow the path of a single instruction

floatobject.c:362

```
/* Comparison is pretty much a nightmare.  When comparing float to float,
 * we do it as straightforwardly (and long-windedly) as conceivable, so
 * that, e.g., Python x == y delivers the same result as the platform
 * C x == y when x and/or y is a NaN.
 * When mixing float with an integer type, there's no good *uniform* approach.
 * Converting the double to an integer obviously doesn't work, since we
 * may lose info from fractional bits.  Converting the integer to a double
 * also has two failure modes:  (1) an int may trigger overflow (too
 * large to fit in the dynamic range of a C double); (2) even a C long may have
 * more bits than fit in a C double (e.g., on a 64-bit box long may have
 * 63 bits of precision, but a C double probably has only 53), and then
 * we can falsely claim equality when low-order integer bits are lost by
 * coercion to double.  So this part is painful too.
 */

static PyObject*
float_richcompare(PyObject *v, PyObject *w, int op)
{
    double i, j;
    int r = 0;

    assert(PyFloat_Check(v));
    i = PyFloat_AS_DOUBLE(v);

    /* Switch on the type of w.  Set i and j to doubles to be compared,
```

# Let's take a deep breath..

- That's *a lot* of code for something so simple.




- Inherent compromise of an interpreted language.
- Overheads usually negligible when the operation does more work.
- Let's try to get closer to the metal (*silicon*, in this case).

**MidJourney**: *a group of university students in a lecture hall taking a deep breath*

# First version in C++

```
float psum_0(float *x, size_t size) {
    float r { 0.f };

    for (size_t i = 0; i < size; ++i) {
        if (x[i] >= 0) {
            r += x[i];
            if (std::isinf(r))
                abort();
        }
    }

    return r;
}
```

Everything has types!

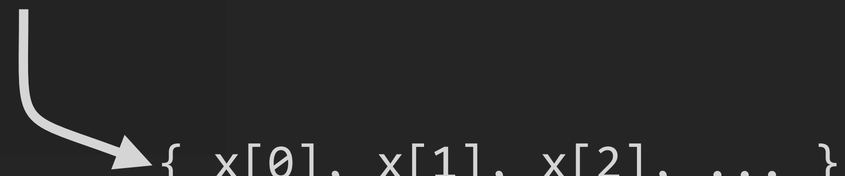
`float`: single precision FP value

`size_t`: 64-bit integer

`std::isinf(x)` – is "x" infinity?

`abort()`: terminate the program.

`float*` x: pointer to a float array



# Python bindings

## Shamesless advertisement

- The details here aren't super-important.
- Need to "glue" C++ and Python code together, which is done using the nanobind library developed by me.


https://nanobind.readthedocs.io/en/latest/

```cpp
#include <nanobind/ndarray.h>

NB_MODULE(psum, m) {
    namespace nb = nanobind;

    using Array = nb::ndarray<float, nb::shape<nb::any>, nb::c_contig>;

    m.def("psum_0", [](Array a) { return psum_0(a.data(), a.shape(0)); })
     .def("psum_1", [](Array a) { return psum_1(a.data(), a.shape(0)); })
     .def("psum_2", [](Array a) { return psum_2(a.data(), a.shape(0)); })
     .def("psum_3", [](Array a) { return psum_3(a.data(), a.shape(0)); });
}
```

# Demo time

# Meaning of "vectorization" in Python

**We will shortly see another meaning of that word as well..**

Bad:

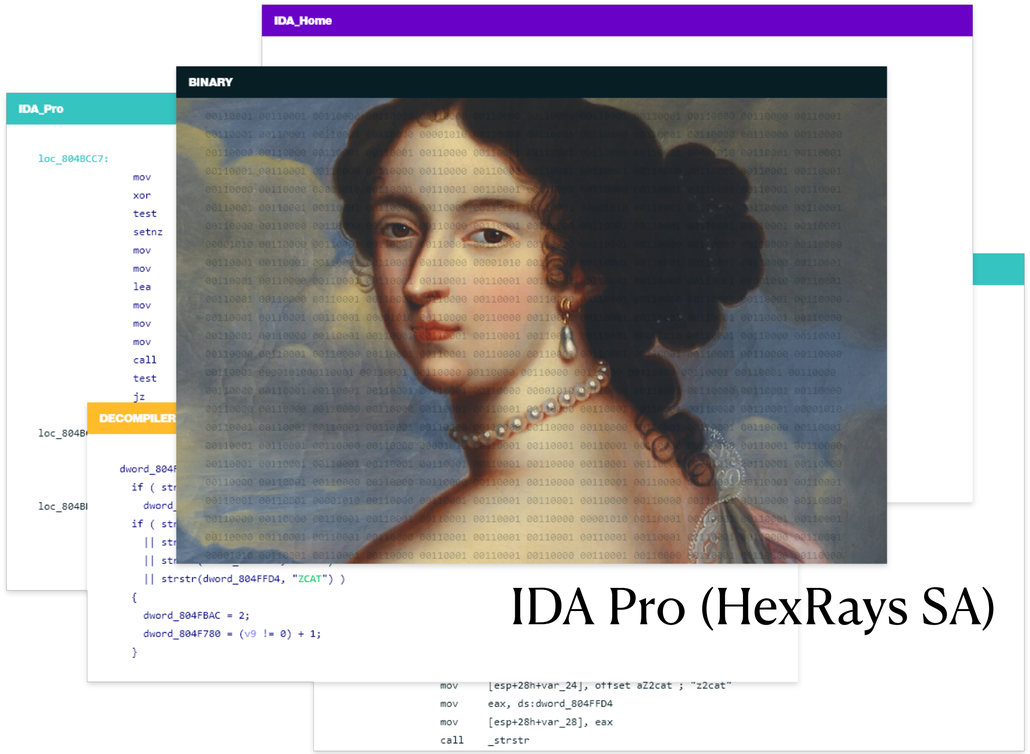
```
for i in range(len(A)):
    if B[i] < 0:
        X[i] = A[i] + C[i]
    else:
        X[i] = A[i] + D[i]
```

Good:

```
X = A + np.where(B < 0, C, D)
```

# A Disassembler

- Can reveal the processor instructions ("assembly code") in a compiled executable
- Often used for hacking/security analysis.
- We will use it to understand the performance differences between the different **`psum`** variations.




IDA Pro (HexRays SA)

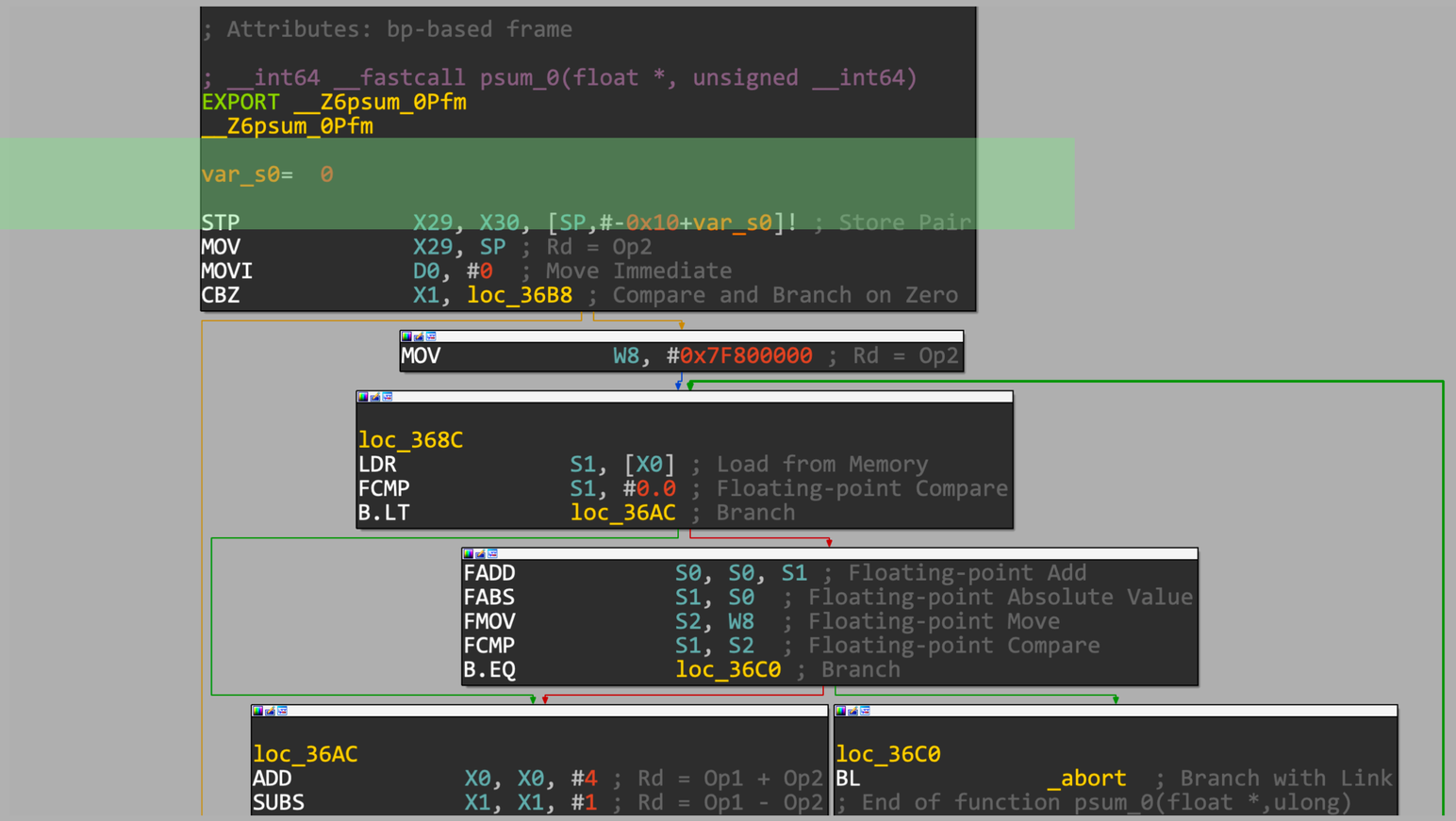
- Freely available: **IDA Home** (https://hex-rays.com/ida-free/, Intel processors only), Open source alternative: **Ghidra** (https://ghidra-sre.org/)

# Demo time

# Disassembly of `psum_0` – in flat form

```
                ; =============== S U B R O U T I N E =======================================

                ; Attributes: bp-based frame

                ; __int64 __fastcall psum_0(float *, unsigned __int64)
                                EXPORT __Z6psum_0Pfm
                __Z6psum_0Pfm                           ; CODE XREF: sub_3968+5C↓p

                var_s0          =  0

FD 7B BF A9                     STP             X29, X30, [SP,#-0x10+var_s0]! ; Store Pair
FD 03 00 91                     MOV             X29, SP ; Rd = Op2
00 E4 00 2F                     MOVI            D0, #0  ; Move Immediate
A1 01 00 B4                     CBZ             X1, loc_36B8 ; Compare and Branch on Zero
08 F0 AF 52                     MOV             W8, #0x7F800000 ; Rd = Op2

                loc_368C                                ; CODE XREF: psum_0(float *,ulong)+3C↓j
01 00 40 BD                     LDR             S1, [X0] ; Load from Memory
28 20 20 1E                     FCMP            S1, #0.0 ; Floating-point Compare
CB 00 00 54                     B.LT            loc_36AC ; Branch
00 28 21 1E                     FADD            S0, S0, S1 ; Floating-point Add
01 C0 20 1E                     FABS            S1, S0  ; Floating-point Absolute Value
02 01 27 1E                     FMOV            S2, W8  ; Floating-point Move
20 20 22 1E                     FCMP            S1, S2  ; Floating-point Compare
C0 00 00 54                     B.EQ            loc_36C0 ; Branch

                loc_36AC                                ; CODE XREF: psum_0(float *,ulong)+1C↑j
00 10 00 91                     ADD             X0, X0, #4 ; Rd = Op1 + Op2
21 04 00 F1                     SUBS            X1, X1, #1 ; Rd = Op1 - Op2
C1 FE FF 54                     B.NE            loc_368C ; Branch

                loc_36B8                                ; CODE XREF: psum_0(float *,ulong)+C↑j
FD 7B C1 A8                     LDP             X29, X30, [SP+var_s0],#0x10 ; Load Pair
C0 03 5F D6                     RET                     ; Return from Subroutine
                ; ---------------------------------------------------------------------------

                loc_36C0                                ; CODE XREF: psum_0(float *,ulong)+30↑j
BB 01 00 94                     BL              _abort  ; Branch with Link
                ; End of function psum_0(float *,ulong)


                ; =============== S U B R O U T I N E =======================================
```

# Disassembly of `psum_0` – in graph form



# A real-life analogy: laundry day!

- It's time to do the laundry: we have 3 batches
  - **Dark**, Light, Color
  - Three steps: **Wash**, **Dry**, **Fold**
  - Time is precious, let's do this *efficiently*!







Time

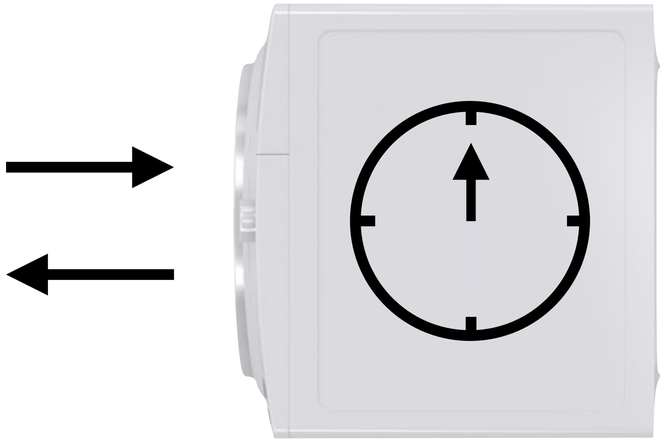
| Wash | Dry | Fold |
|---|---|---|
| Dark | | |
| Light | Dark | |
| Color | Light | Dark |
| | Color | Light |
| | Light | |
| | | Light |
| Color | | |
| | Color | |
| | | Color |

**Naïve** schedule: 9 cycles
**Better** schedule: 4 cycles

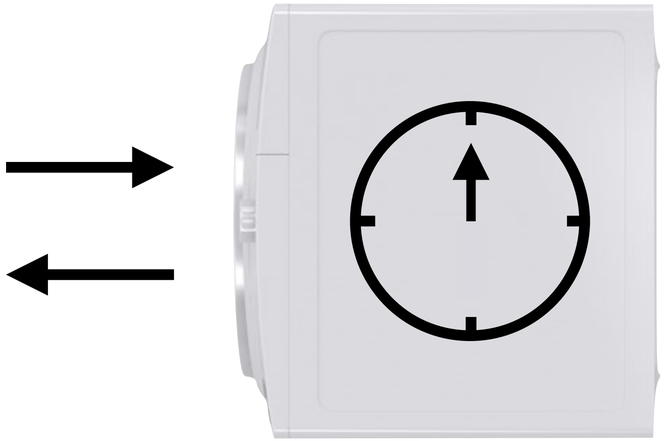
**MidJourney**: 1. three baskets full of laundry, one black, one white, one colored. isometric, white background. comic style 2. vector drawing of different types of washing and drying machines. 3. hands folding clothes, comic style on white background.

# Latency and Throughput

Latency: 1, Throughput: 1



Latency: 4, Throughput: 1/4

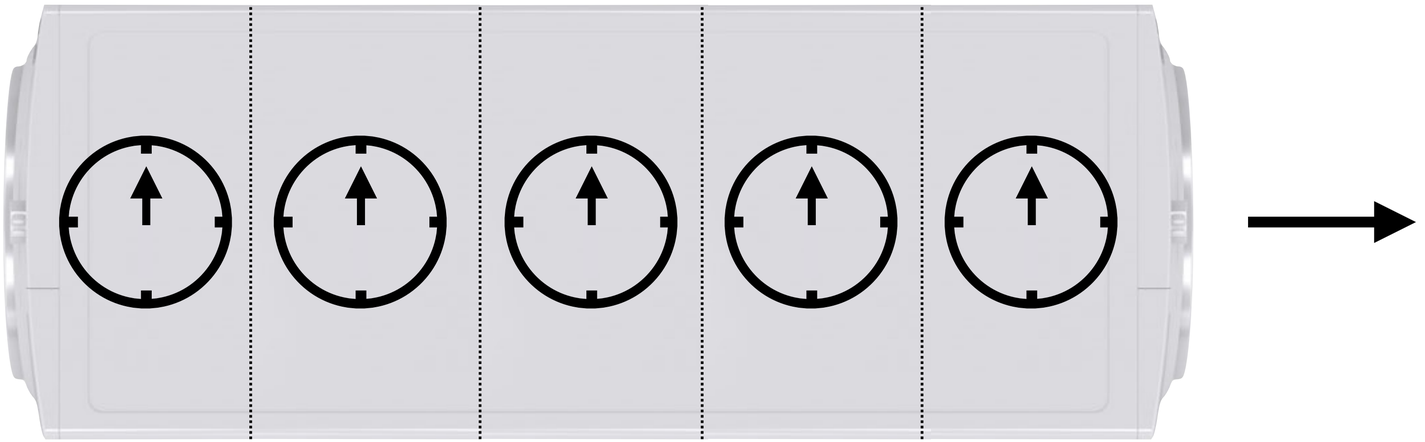




**MidJourney**:.vector drawing of a laundry basket on white background, top-down view

# Pipelining *within* processing units

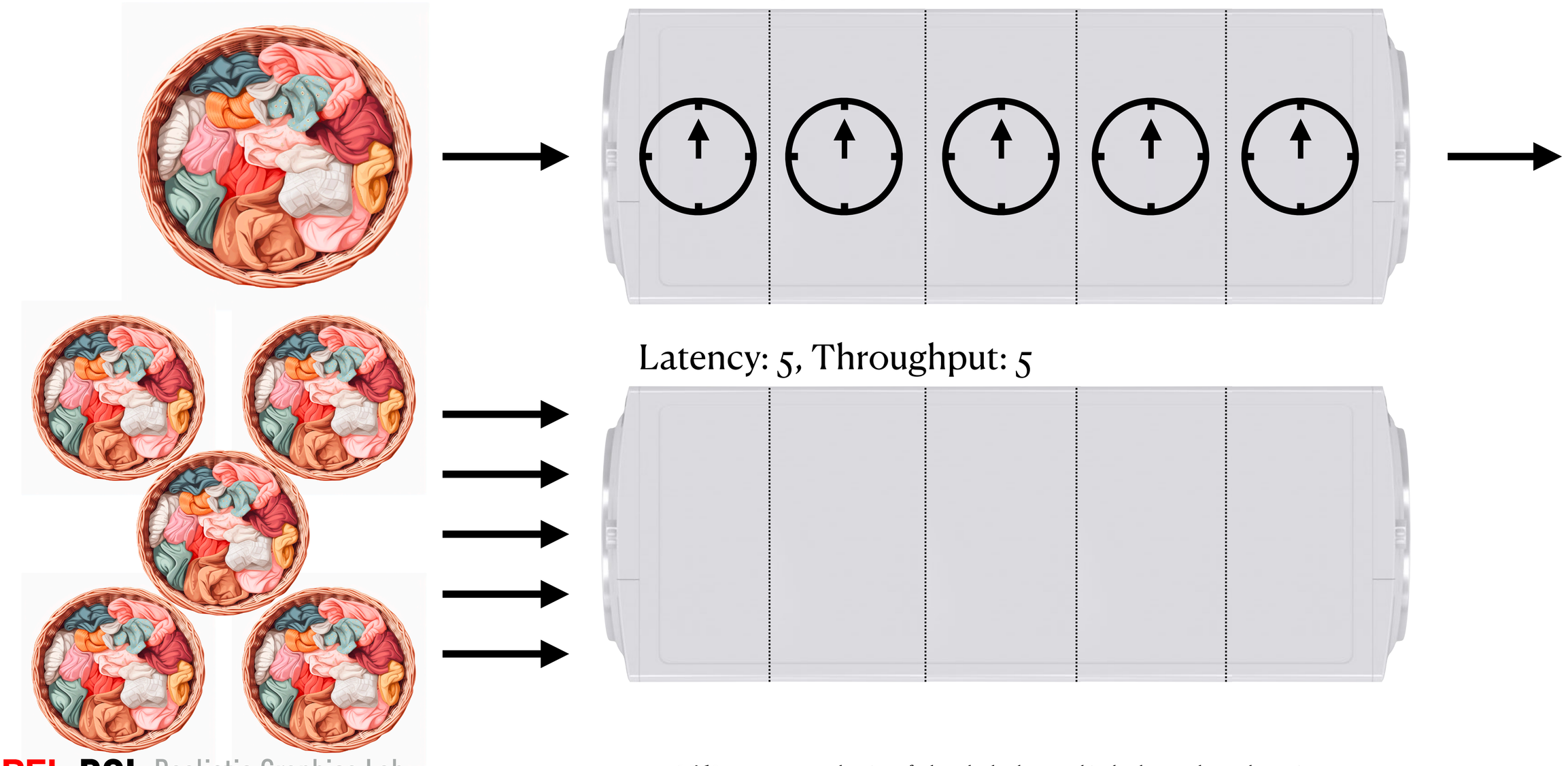
Latency: 5, Throughput: 1





**MidJourney**:.vector drawing of a laundry basket on white background, top-down view

# Pipelining *within* processing units






**MidJourney**:.vector drawing of a laundry basket on white background, top-down view

# Concrete examples for a real processor

## Example data from the Intel "*Ice Lake*" architecture

- (Clock) **Cycle**: on a 3 Ghz CPU:
  - 1 cycle = 0.33 nanoseconds.
    *Light moves 10 cm in that time.*
- **Latency**:
  - 1 means: start an addition, result immediately available on the next cycle.
  - >1 means: need to wait several cycles.
- **Throughput**:
  - 4 means: can start 4 additions every cycle!
  - 1/14 means: busy for 14 cycles before new input can be accepted.
    **Loading** memory, **division**, and **square root** are really expensive operations.

`int64` integers

| Instruction | Latency | Throughput |
|---|---|---|
| `add, sub` | 1 | 4 |
| `mul` | 3 | 1 |
| `div` | 15 | 1/14 |

`float32` vectors

| | | |
|---|---|---|
| `add, sub, mul` | 4 | 2 |
| `div` | 17 | 1/10 |



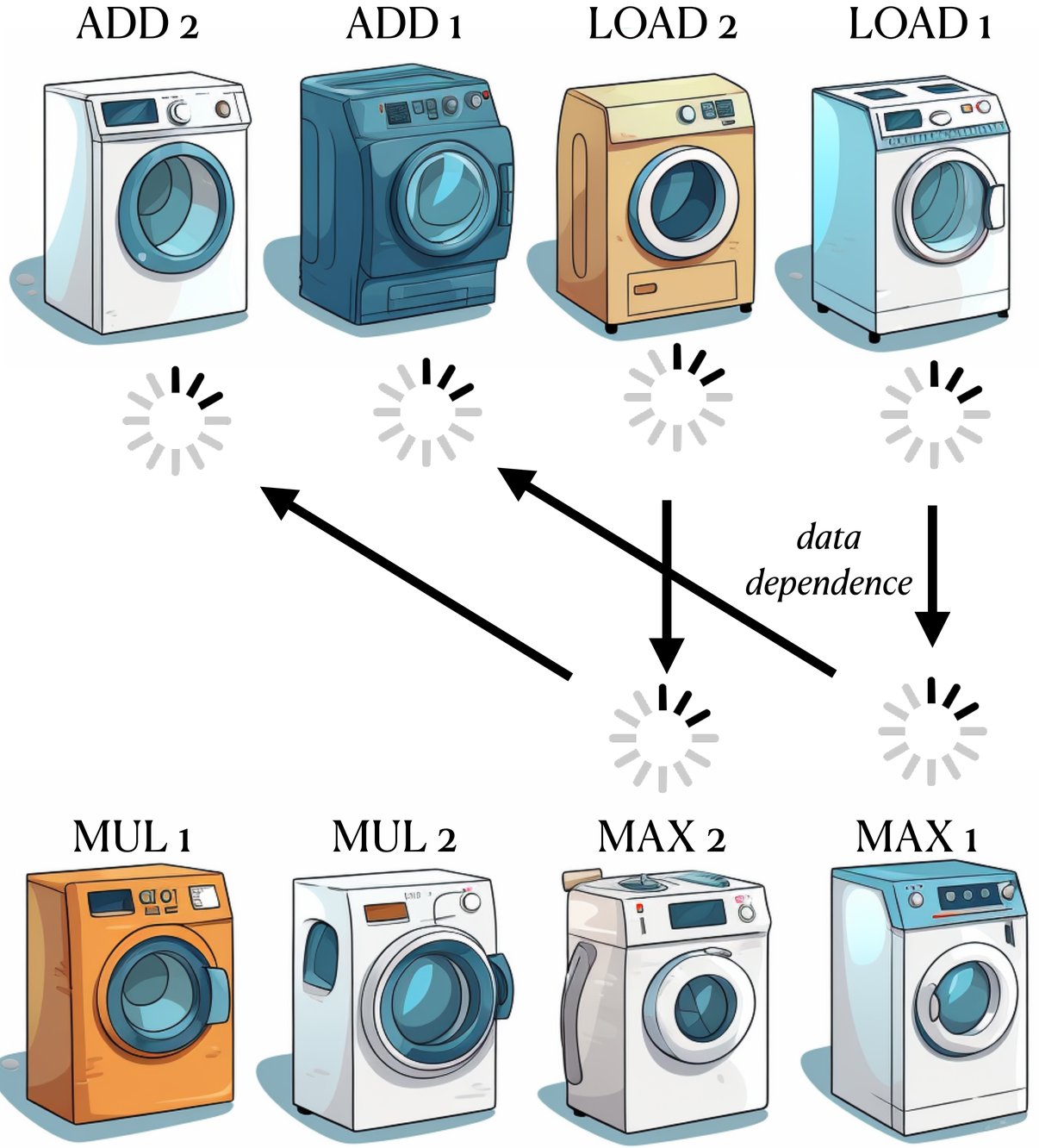
**MidJourney**:.vector drawing of a laundry basket on white background, top-down view

# Tomasulo's algorithm

**aka. "Superscalar execution"**

- *Aggressively parallelizes* the execution of a program. Instead of running it step after step, try to detect what can be run while respecting data dependencies.
- Processing must wait for inputs to be ready ("reservation stations").
- LOADs are **extremely** slow, helpful to do multiple in parallel.
- Newer architectures (e.g. Apple M1) look at the eight (8!! 🤯) next instructions *per clock cycle*. In a loop, can run ahead several iterations 🤯🤯.


d = d + c  c = max(b, 0.0)  b = a[d]






**MidJourney**: vector drawing of different types of washing and drying machines

# The CPU seen as a high-speed train

## To keep the pipeline fed, processor must look far ahead

```
00000000  C5 F8 57 C0 48 85 FF 74 20 0F 1F 80 00 00 00 00
00000010  C5 FA 10 0E C5 F2 59 0A C5 FA 58 C1 48 83 C2 04
00000020  48 83 C6 04 48 FF CF 75 E7 C3 ?? ?? ?? ?? ??  .
00000030  . . . . . . . . . . . . . . . . . . . . . . . .
```

**Executing** `C5 F8 57 C0`**:**

```
xorps xmm0, xmm0, xmm0
```

**Scheduling** `48 85 FF 74 20`**:**

```
test  rdi, rdi
jz loop_end
```

**Decoding** `0F 1F 80 00 00 00 00 C5 FA 10 0E`**:**

```
???????
???????
???????
```

**MidJourney**: High speed train driving along a rail track. The driver in the cockpit looks through binoculars to observe obstacles far ahead.

# Branch prediction

- Every time your program contains a branch instruction, processor must decide what to do a long time in advance!
  - *To jump, or not to jump?* Waiting for the actual answer would be **too slow**.

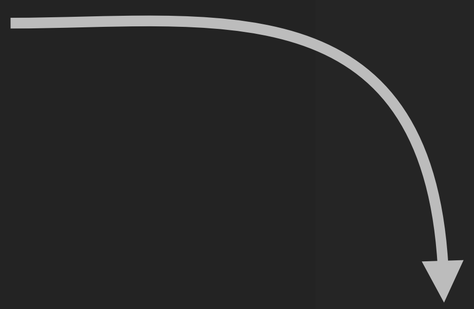
- **The Algorithm**:
  - Ask the oracle: jump or not?
  - Go that way & hope it's correct! Begin executing the instructions.
  - N clock cycles later, we will know if it was the right decision.
    - Correct? All good. 😊
    - Wrong? 😱 PANIC!!! Let's pull the emergency break, and undo all steps.


In our naïve implementation, this happens all the time!
Values are random & positive with 50% probability...

```
# Generate a huge input array of random numbers (4 gigabytes)

n = 1024*1024*1024
x = np.float32(np.random.randn(n))
```

# Improved version

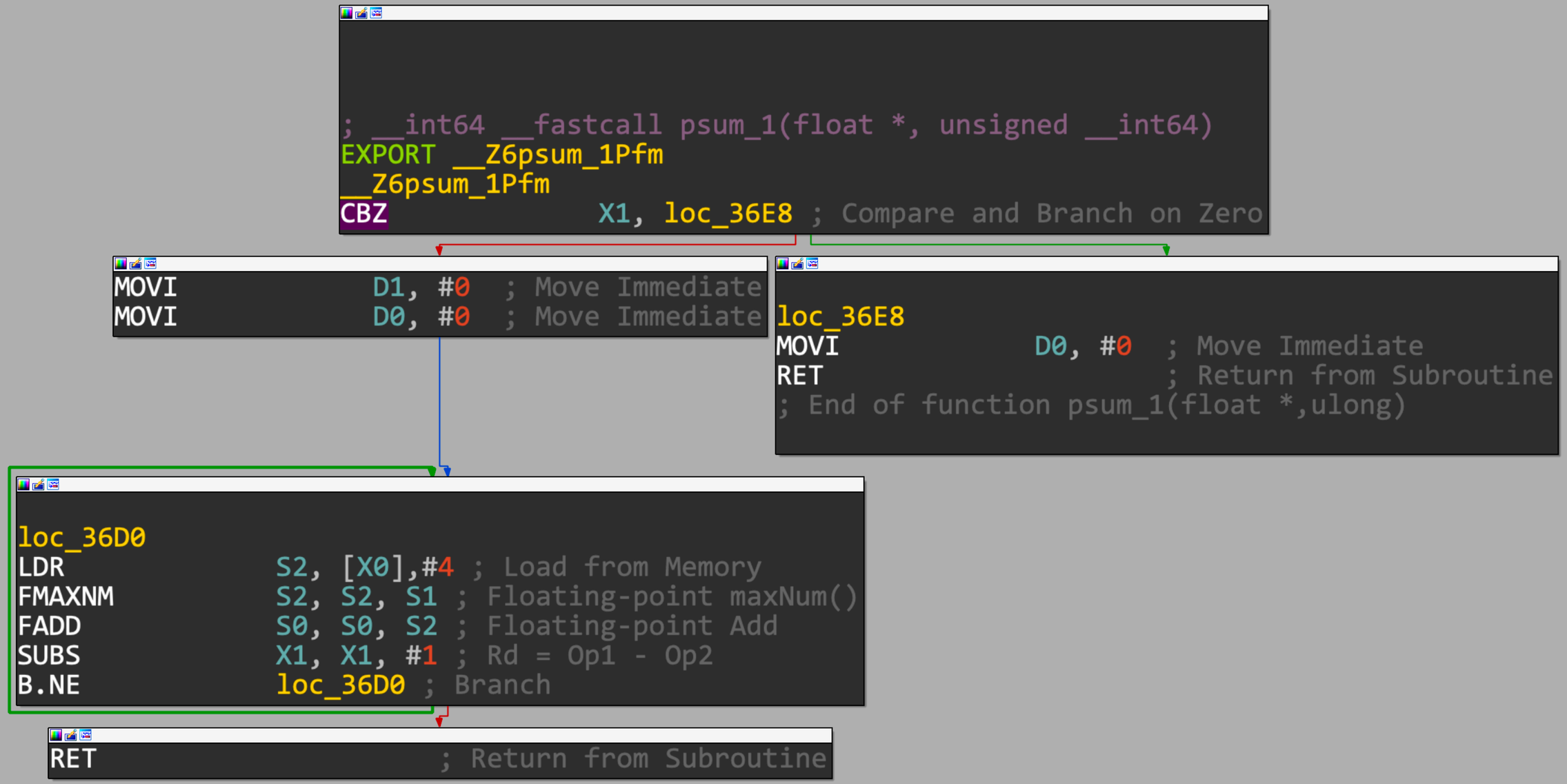
```
float psum_0(float *x, size_t size) {
    float r { 0.f };

    for (size_t i = 0; i < size; ++i) {
        if (x[i] >= 0) {
            r += x[i];
            if (std::isinf(r))
                abort();
        }
    }

    return r;
}
```



```
for (size_t i = 0; i < size; ++i)
    r += fmaxf(x[i], 0.f);
```

# Demo time

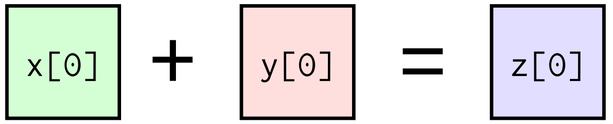
# Disassembly of psum_1



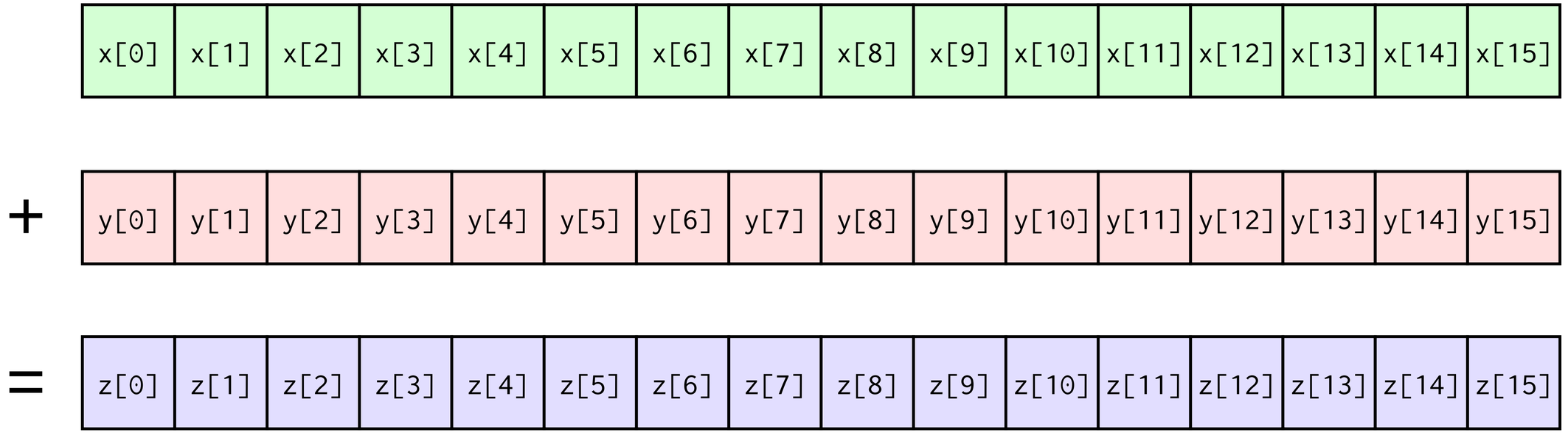
# CPUs can process vectors

**This is known as SIMD (single instruction, multiple data)**

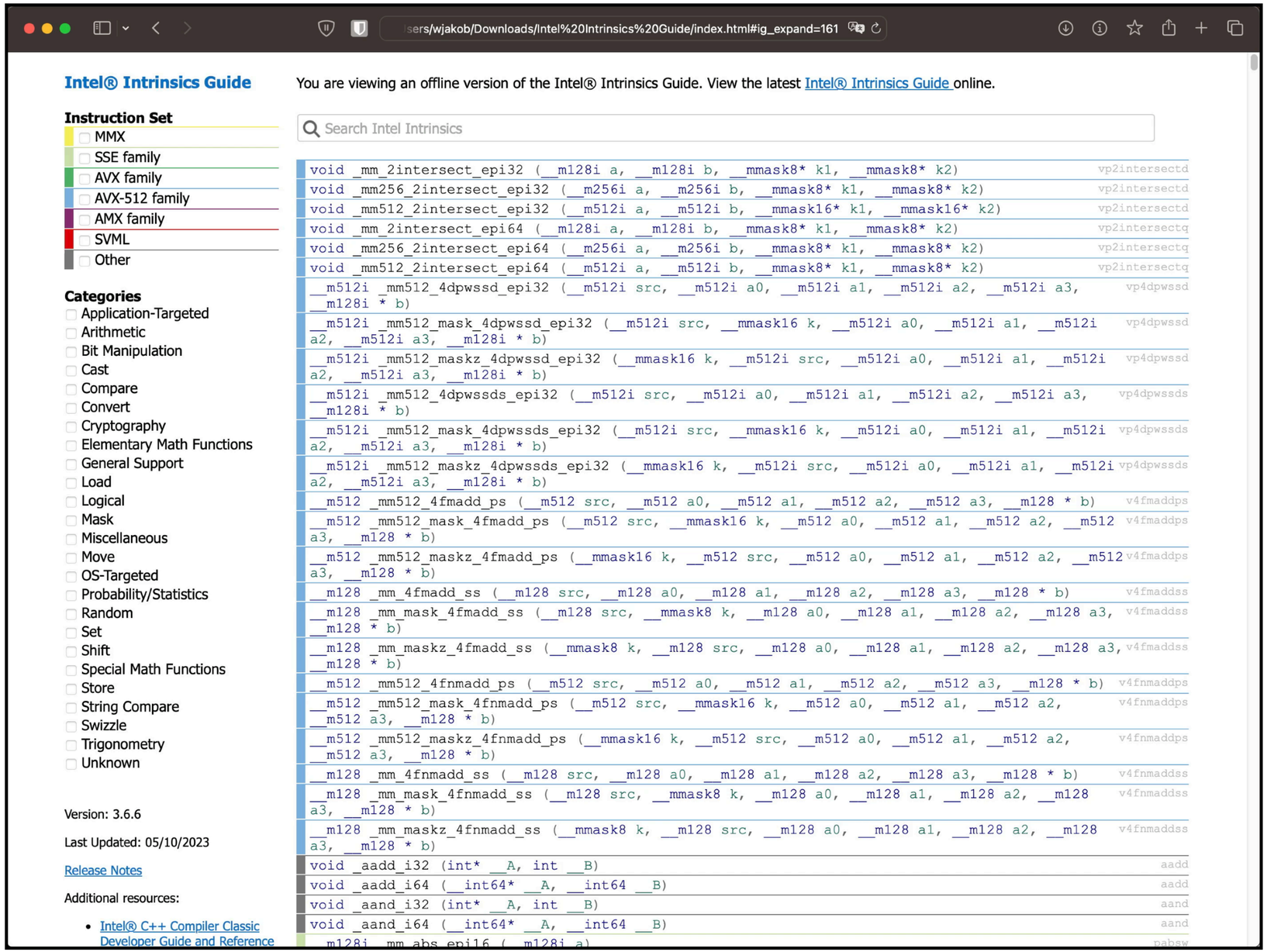
In the same amount of time, can do either ...




... or ...

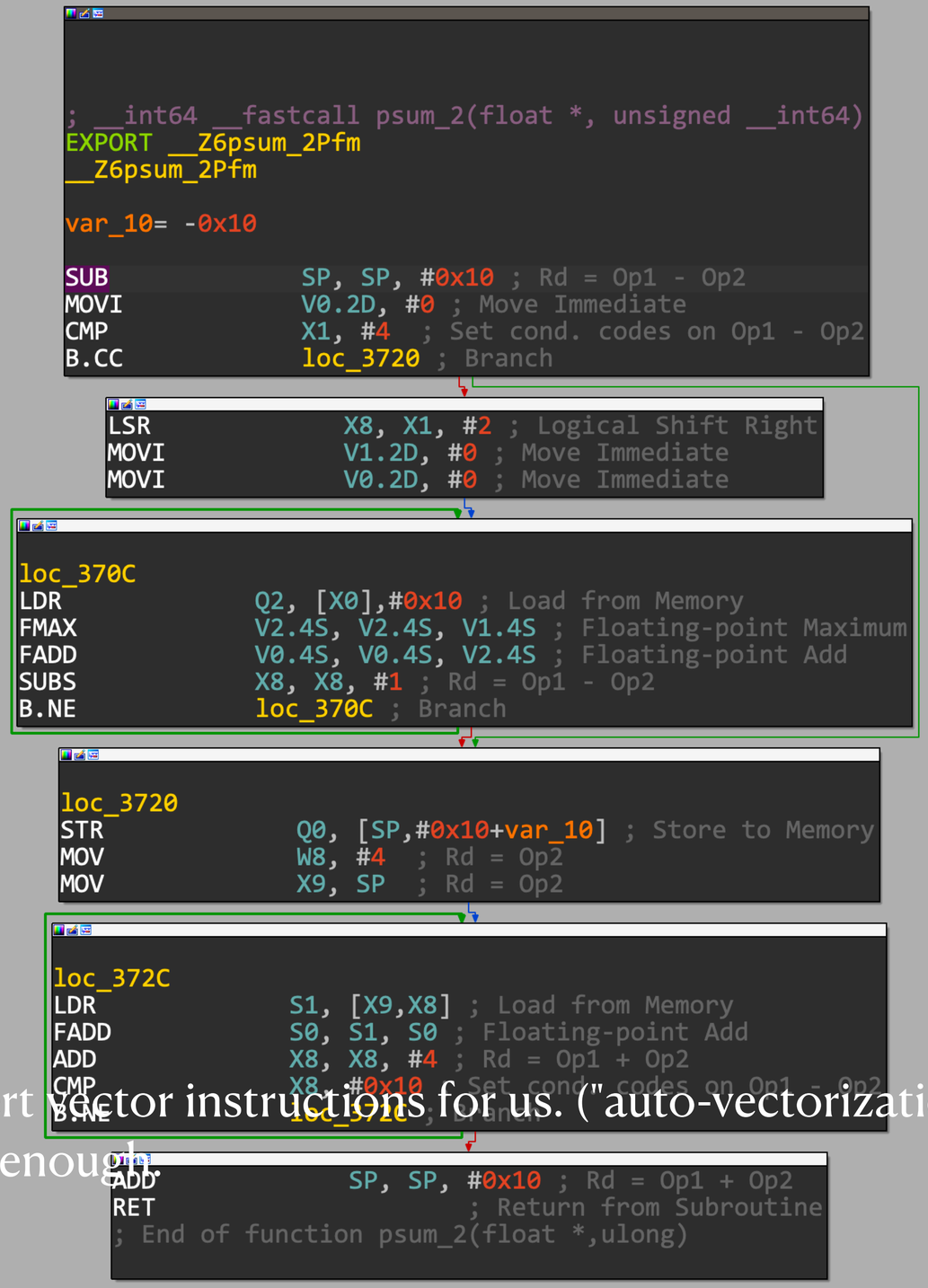


# Intrinsics




**Intel & AMD** SSE, AVX, AVX512— Intrinsics Explorer (link) **ARM**: NEON (link), SVE (datacenter processors, link)

# Disassembly of `psum_2`



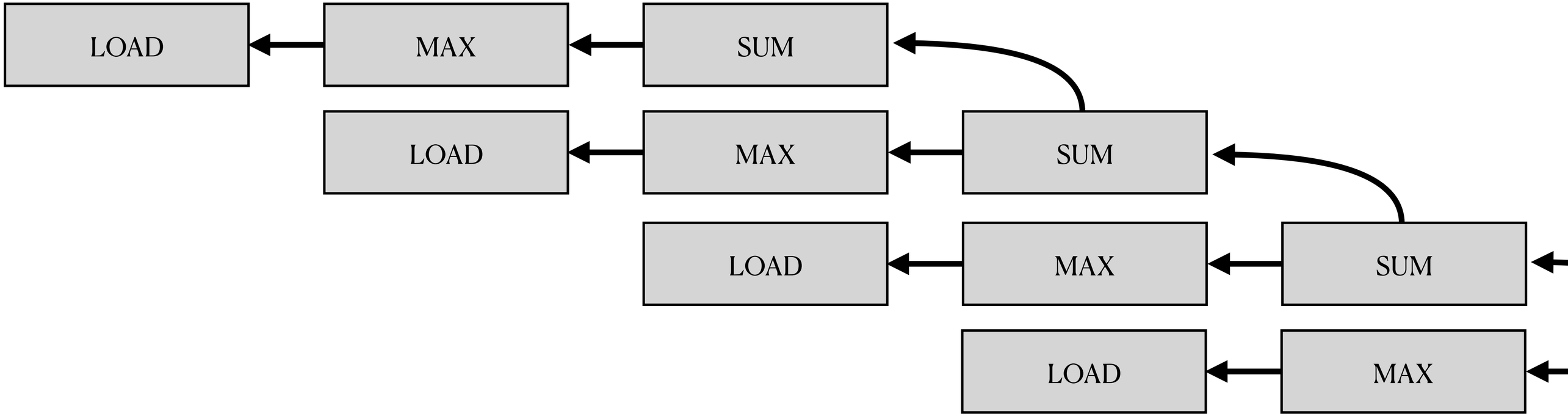

The idea was always that compilers would magically insert vector instructions for us. ("auto-vectorization")

**Sad part**: is never really worked, still does not work well enough.

# Demo time

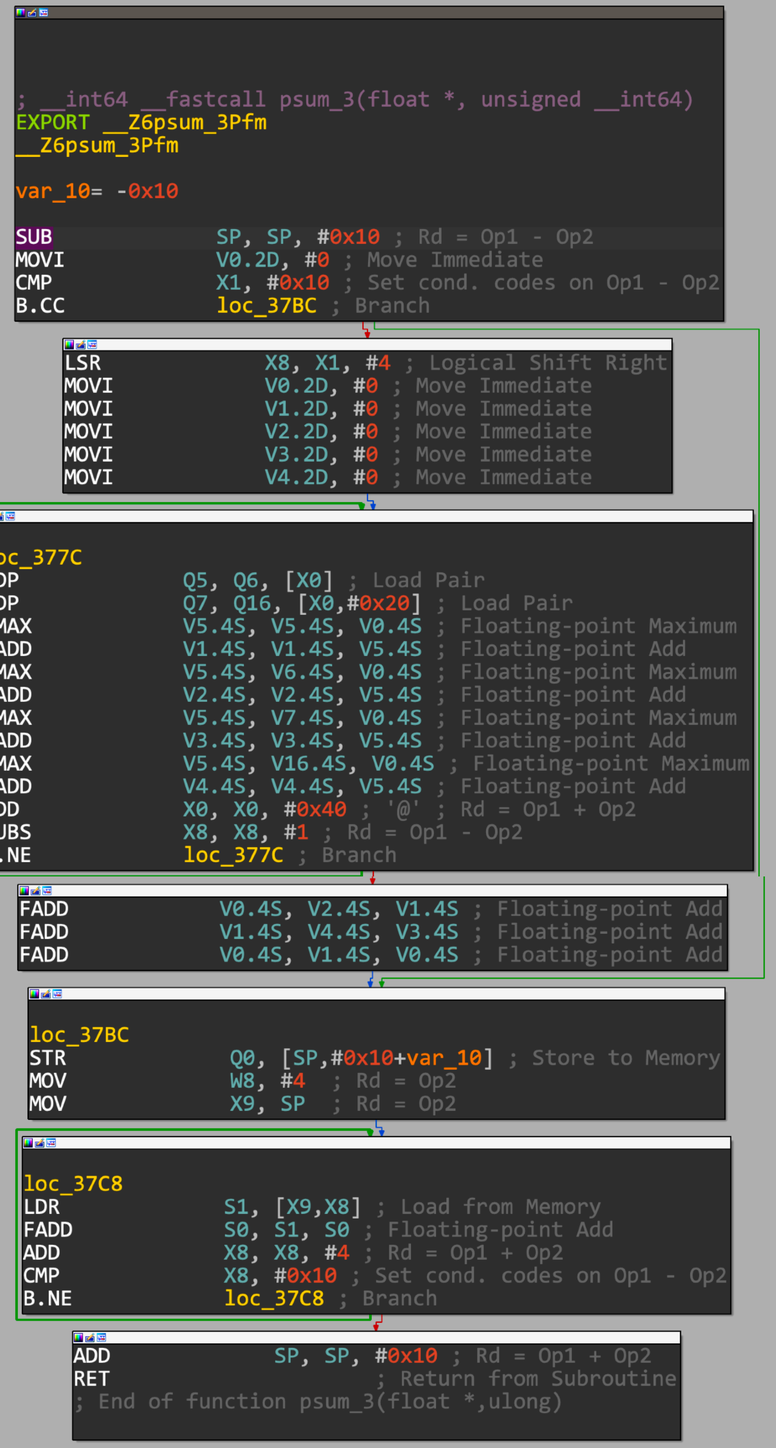
# What's missing?

- Our program is still not parallel enough. Can't keep the pipeline fed.



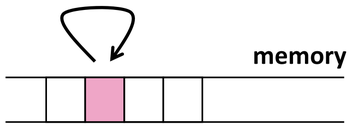

- Break those troublesome connections. We can compute 4 (or 8 or 16) partial sums and then add them up at the end.

# Disassembly of `psum_3`

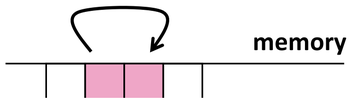


# Memory & Caches

- Load instruction
  **Latency**: ~5-300 cycles
  **Throughput**: 2
- Depends on where we go in the memory hierarchy.

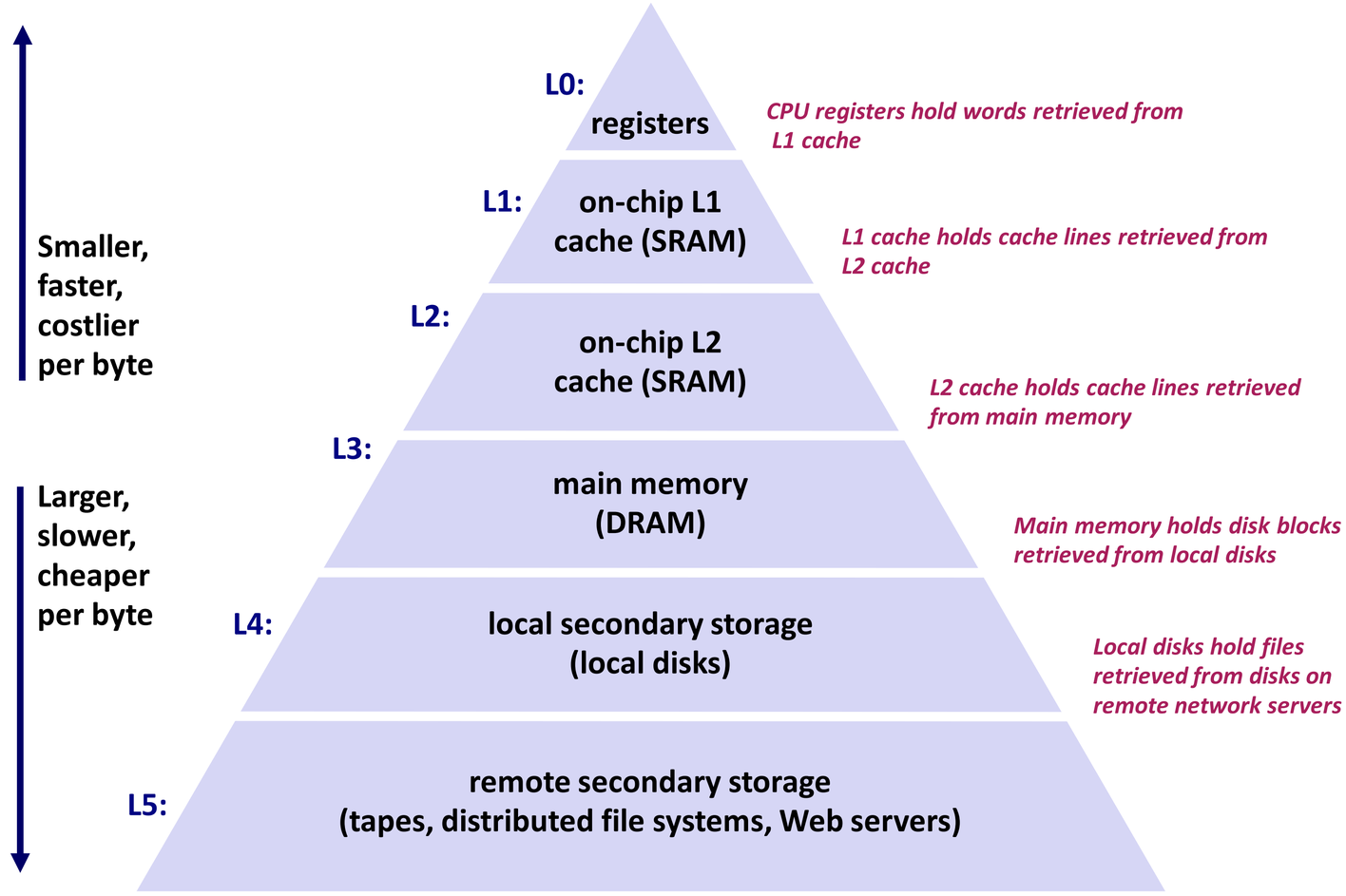



Temporal locality



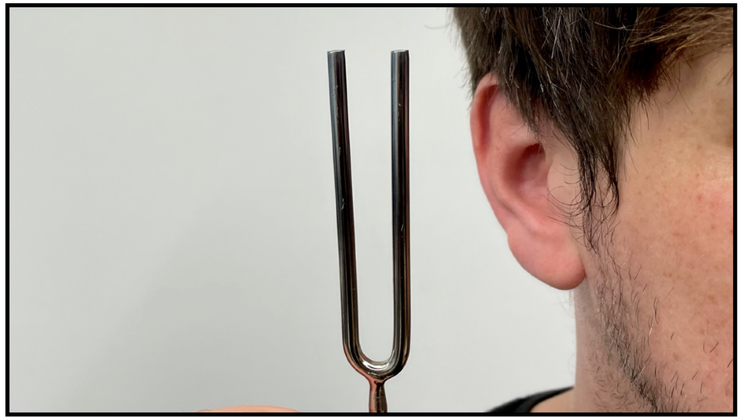

Spatial locality

## Typical Memory Hierarchy

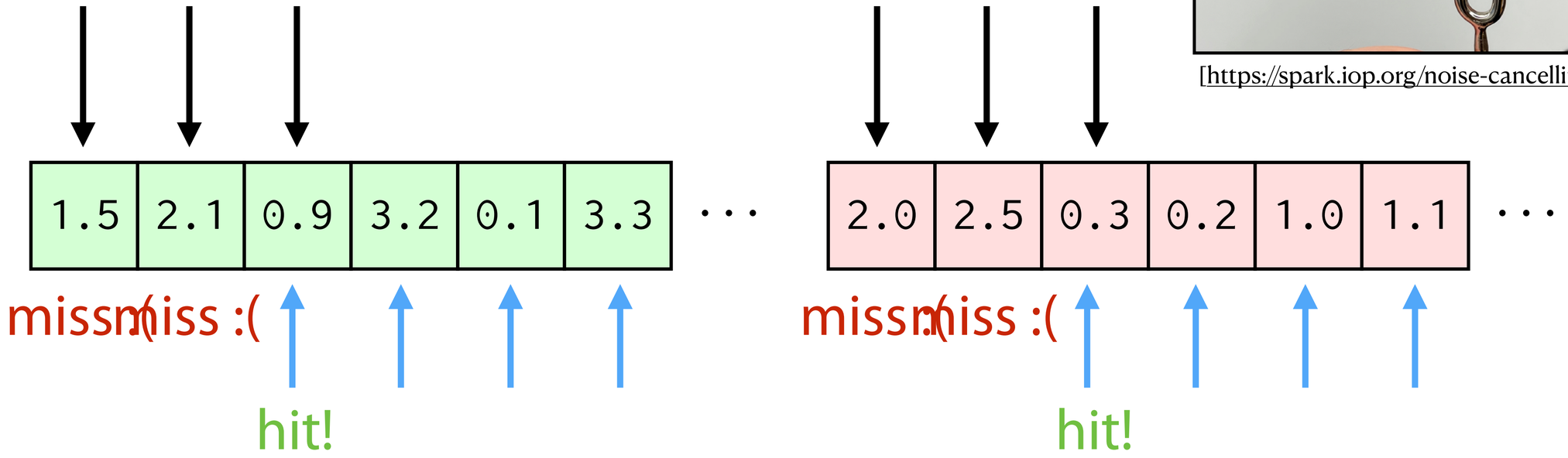



[Markus Püschel, ETHZ

# Prefetchers exploit spatial & temporal regularity



[https://spark.iop.org/noise-cancelling-tuning-fork]



# a

[Images by ChatGPT]


Get something predictable
from the corner store.


Weird unpredictable access,
have to wait for a long time.

# CPUs vs GPUs

- All this fancy stuff
  - issuing multiple instructions per cycle
  - huge caches
  - branch prediction, speculative execution

  .. **GPUs don't have it**!


**MidJourney**: a Cheetah

- If a CPU is a **cheetah** (a product of evolution designed to be super-fast), then a GPU is an **army of snails**.
- Each core much simpler & smaller, but also very slow. In exchange, can have **lots** of them.


**MidJourney**: an army of snails charging forward

# General advice

- **When optimizing something, be wary of**
  - .. sacrificing correctness for speed
    - *Ensure correctness (e.g. via test framework) first*
  - .. reinventing the wheel
    - *Use right tools, libraries, etc.*
  - .. valuing computer time over your own time
    - *Maybe optimization isn't really needed.*

- **Always measure**: most time is spent in a few bottlenecks. Locate them and focus on just this part.

# The end.


AN x64 PROCESSOR IS SCREAMING ALONG AT BILLIONS OF CYCLES PER SECOND TO RUN THE XNU KERNEL, WHICH IS FRANTICALLY WORKING THROUGH ALL THE POSIX-SPECIFIED ABSTRACTION TO CREATE THE DARWIN SYSTEM UNDERLYING OS X, WHICH IN TURN IS STRAINING ITSELF TO RUN FIREFOX AND ITS GECKO RENDERER, WHICH CREATES A FLASH OBJECT WHICH RENDERS DOZENS OF VIDEO FRAMES EVERY SECOND
BECAUSE I WANTED TO SEE A CAT JUMP INTO A BOX AND FALL OVER.
I AM A GOD.
[https://xkcd.com/676]