# Branchless Programming in C++

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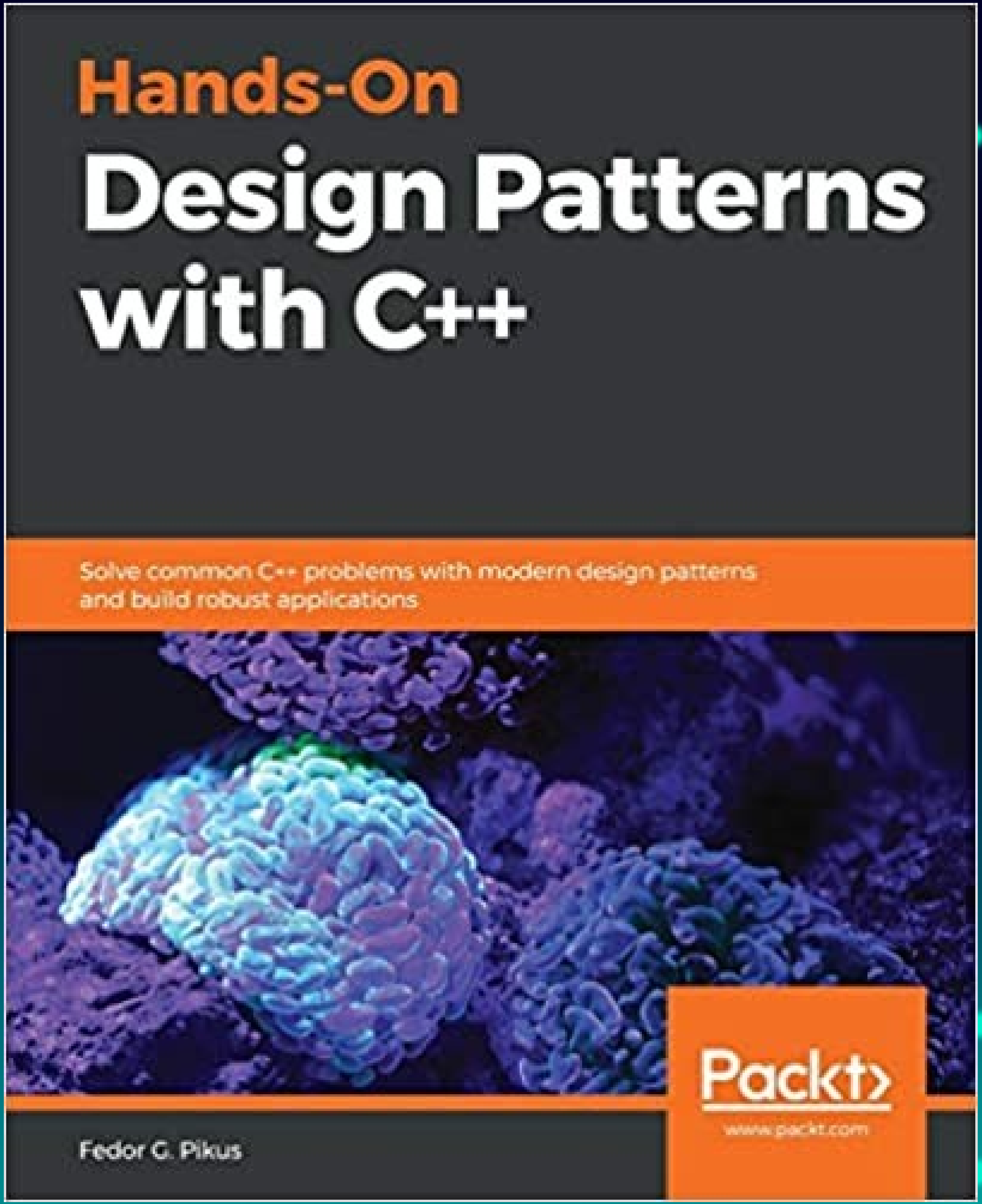
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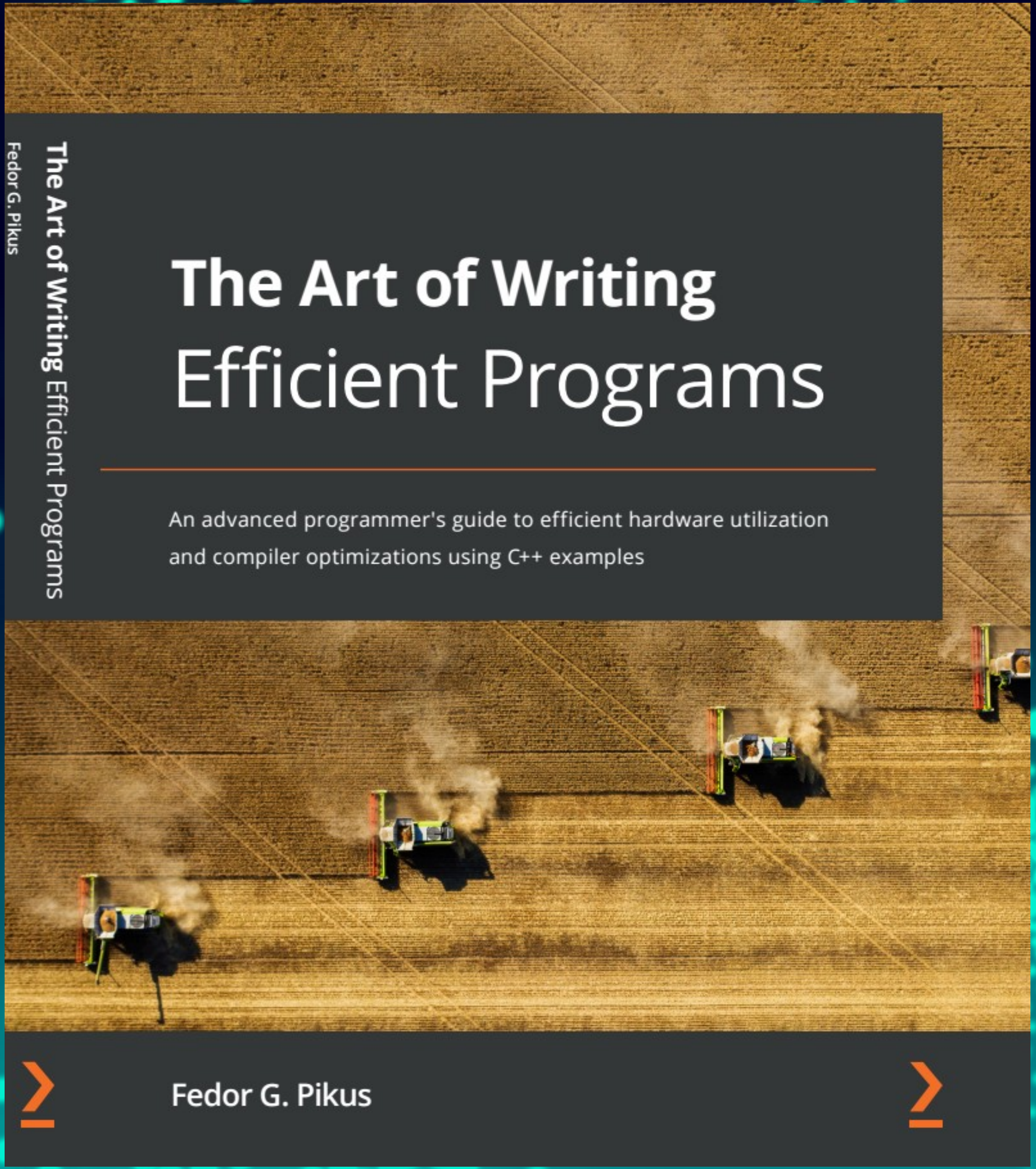
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The Art of Writing
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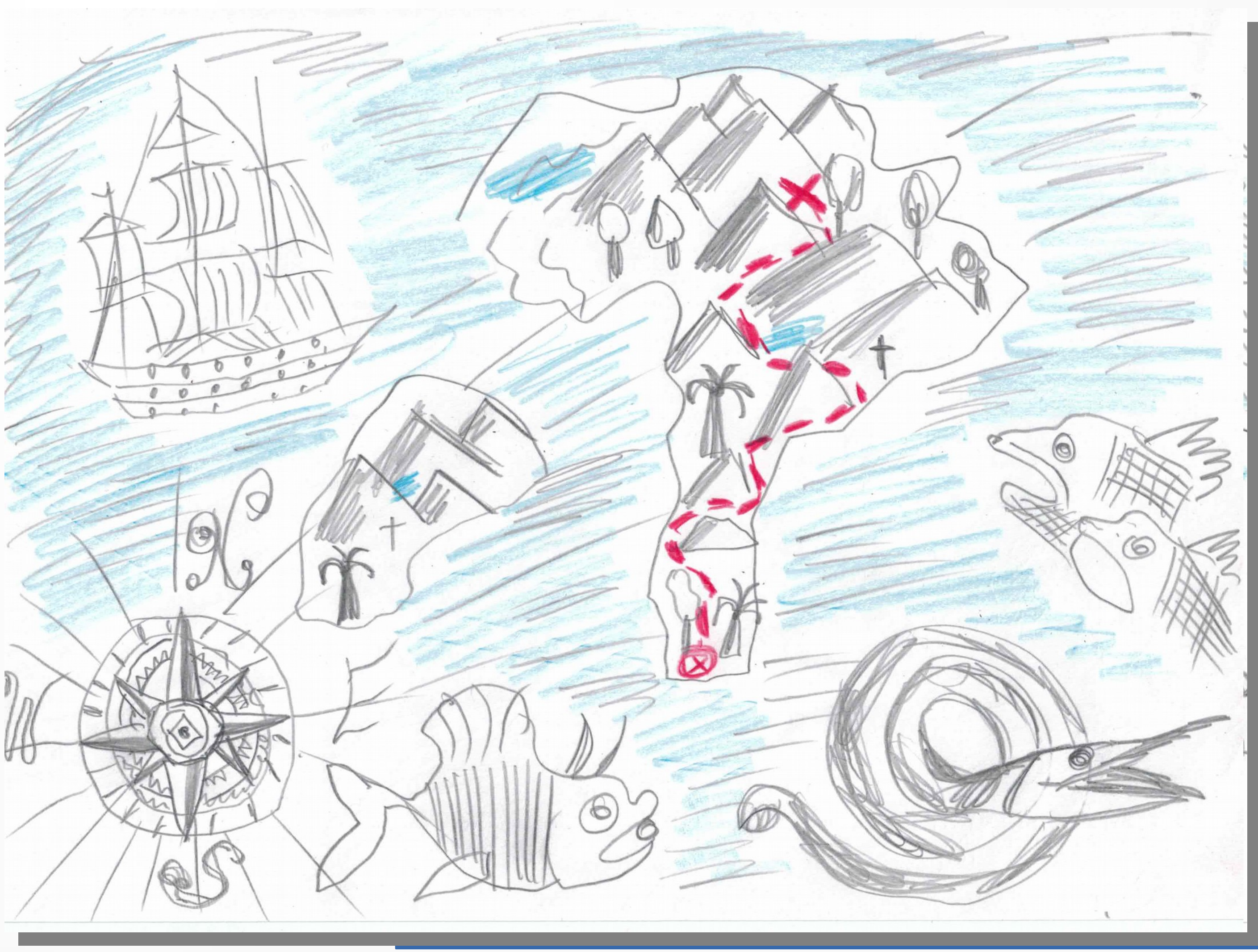
# PLAN

- Efficiency and performance
- Understanding the hardware and using it efficiently
  - Computing resources of a CPU
  - Pipelining
  - Branch prediction and hardware loop unrolling
- Conditional code vs efficiency
- Optimizing conditional code
- Branchless programming



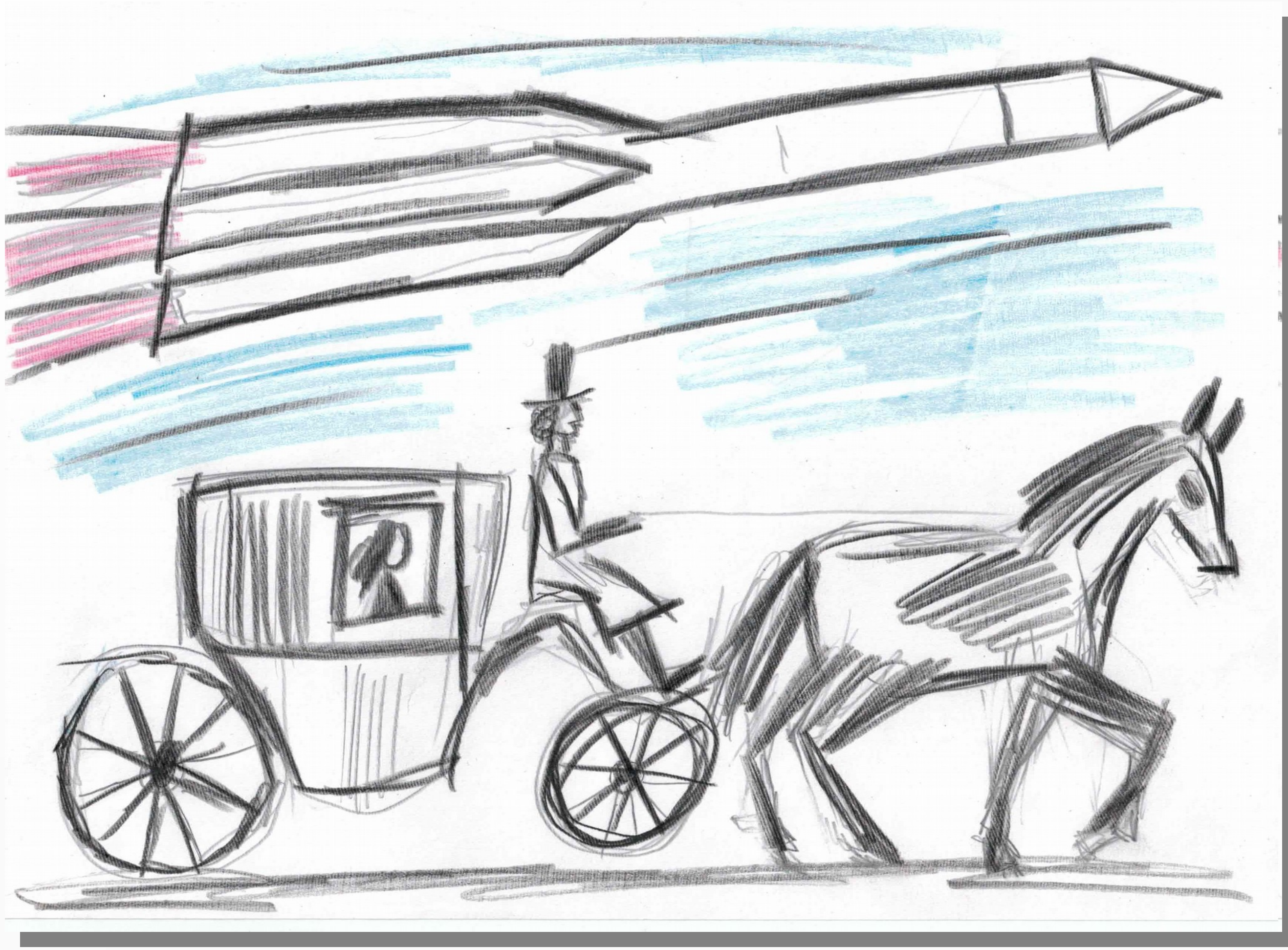
# WHAT CAN BRANCHLESS OPTIMIZATIONS DO?

```
f(bool b, unsigned long x, unsigned long& s) {if (b) s +=x;}
```

- 130M calls/second
- Optimized:
  400M calls/second

```
if (x[i] || y[i]) { … }
```

- 150M evaluations/second
- Optimized:
  570M evaluations/second



# USE ALL OF THE CPU HARDWARE ALL THE TIME

- What determines performance?
- Optimal algorithm:
  - get the result with minimal work
- Efficient use of language:
  - do not do any unnecessary work
- **Efficient use of hardware**
  - **use all available resources**
  - **at the same time**
  - **all the time**



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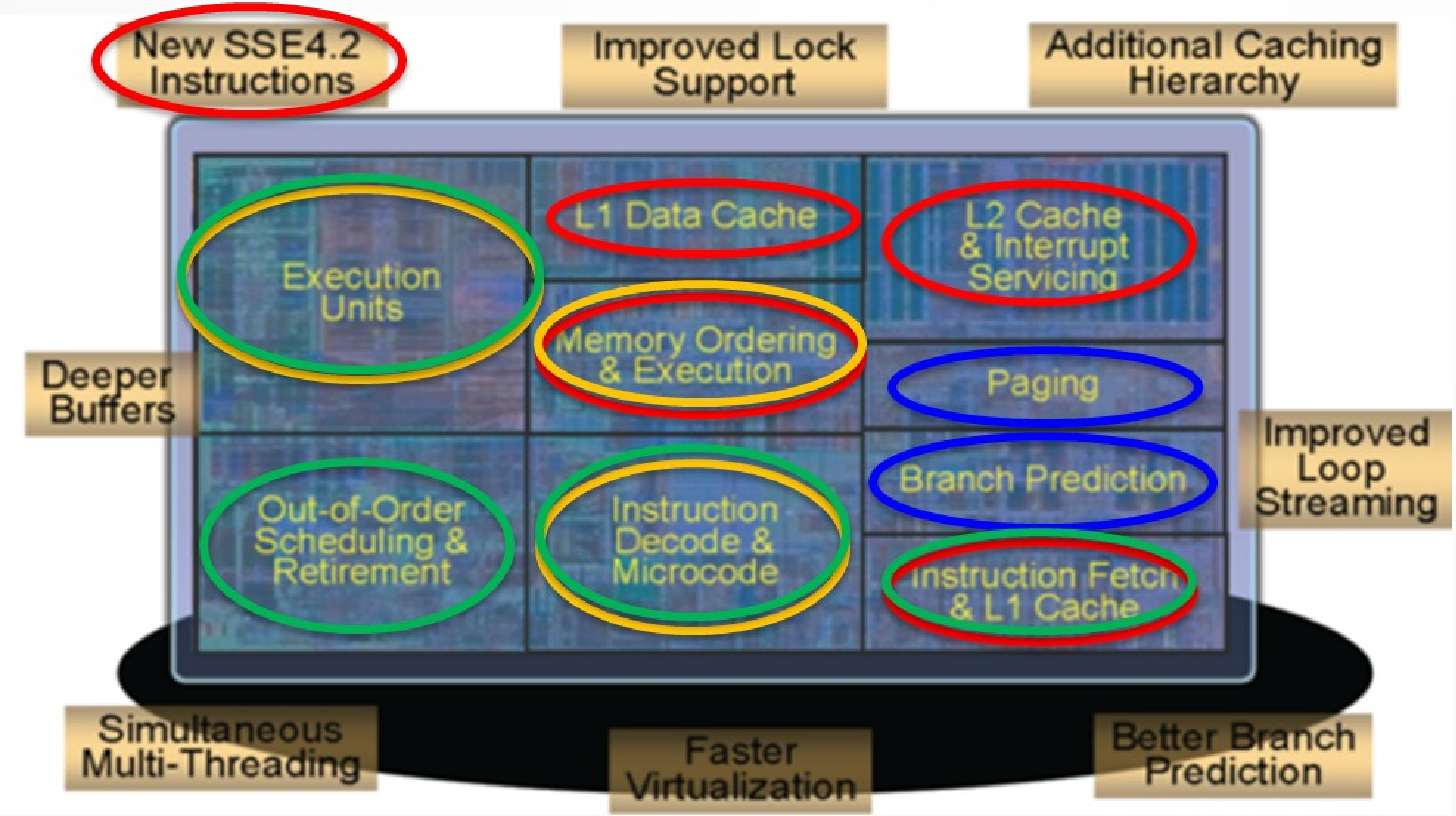
# GLOSSARY OF HARDWARE




- "Just works"
- Compiler takes care of it
- Needs care
- "Just works" but Good to know

# COMPUTING RESOURCES OF A CPU

```
unsigned long v1[N], v2[N];
unsigned long a = 0;
for (size_t i = 0; i < N; ++i)
{
  a += v1[i]*v2[i];
}
```

# COMPUTING RESOURCES OF A CPU

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unsigned long v1[N], v2[N];
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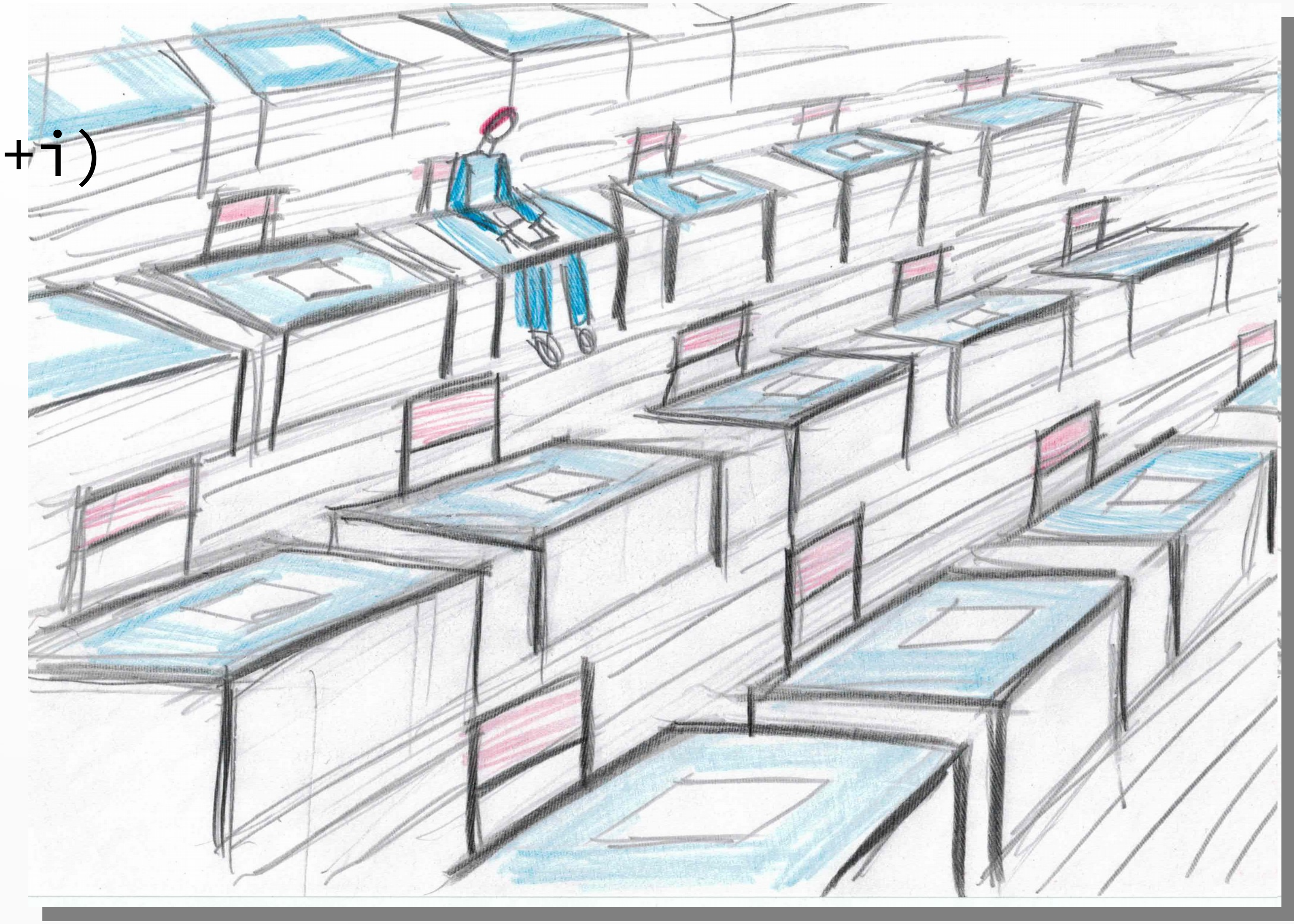
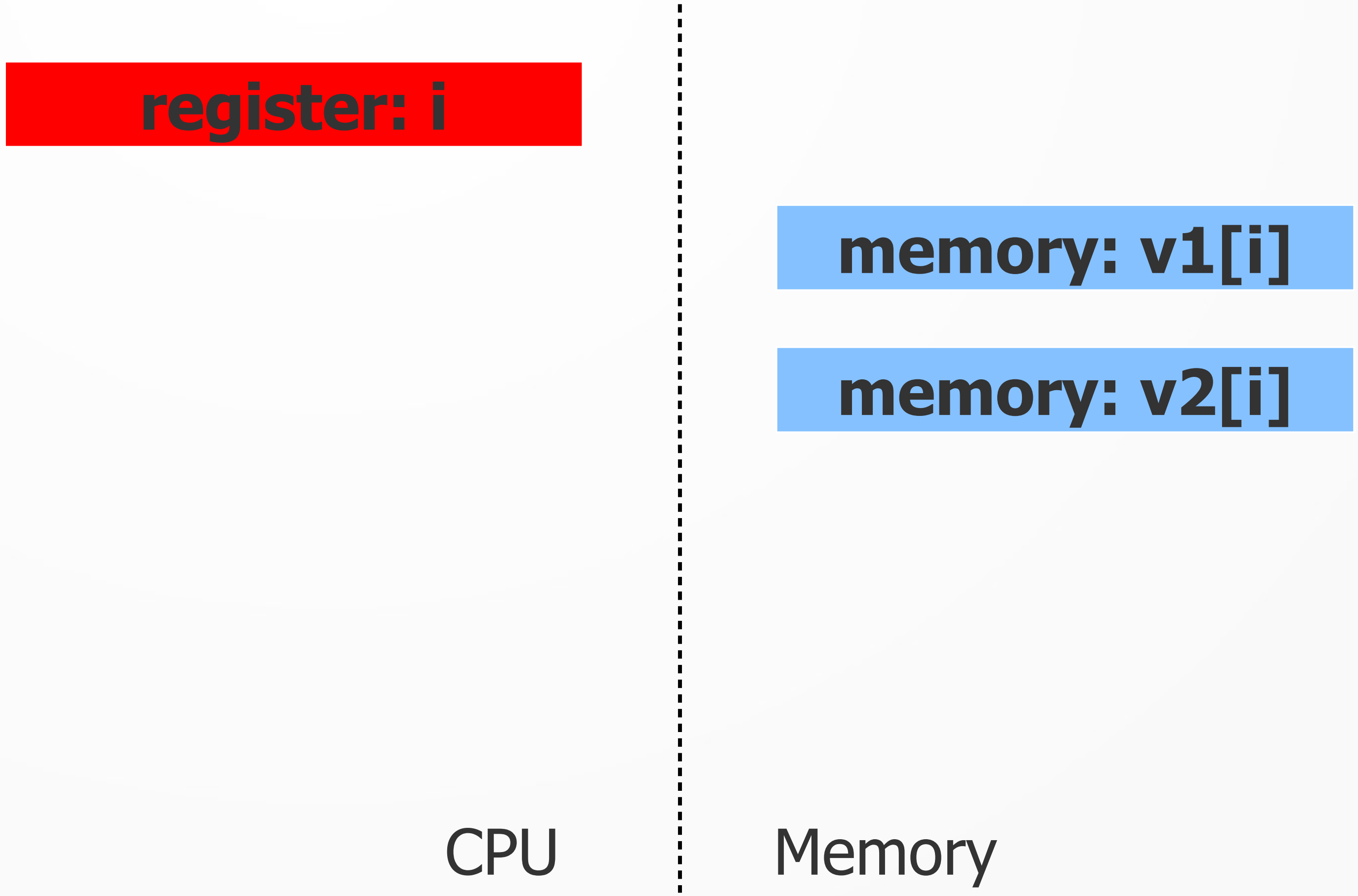
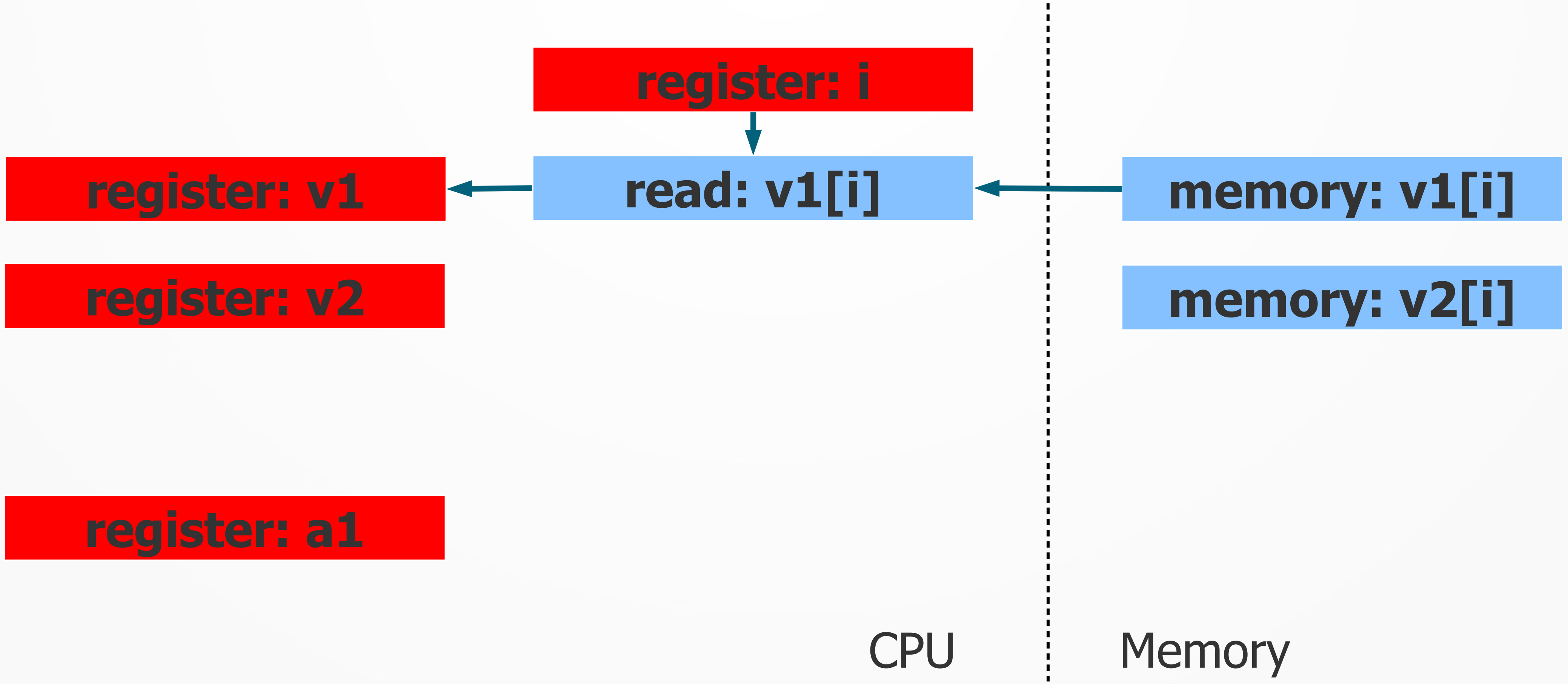


# COMPUTING RESOURCES OF A CPU



# COMPUTING RESOURCES OF A CPU





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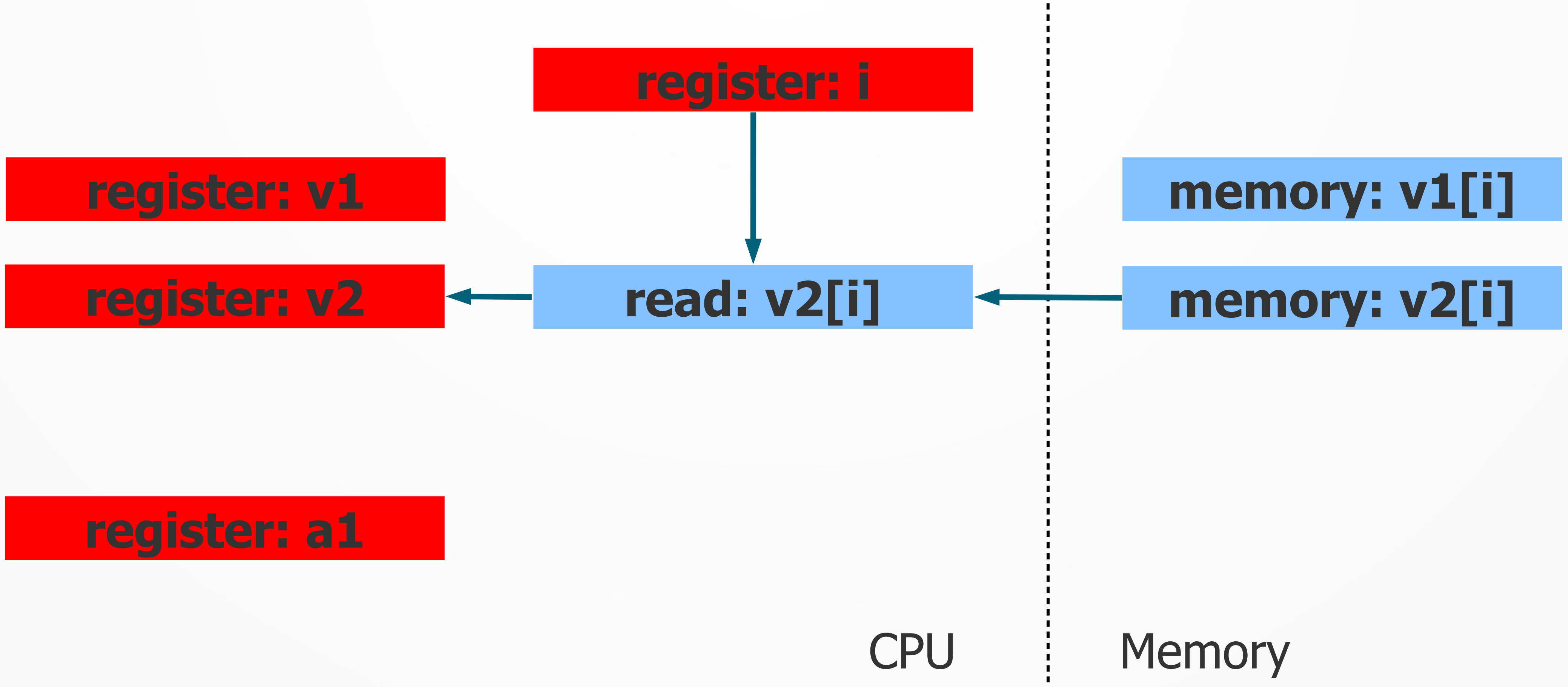
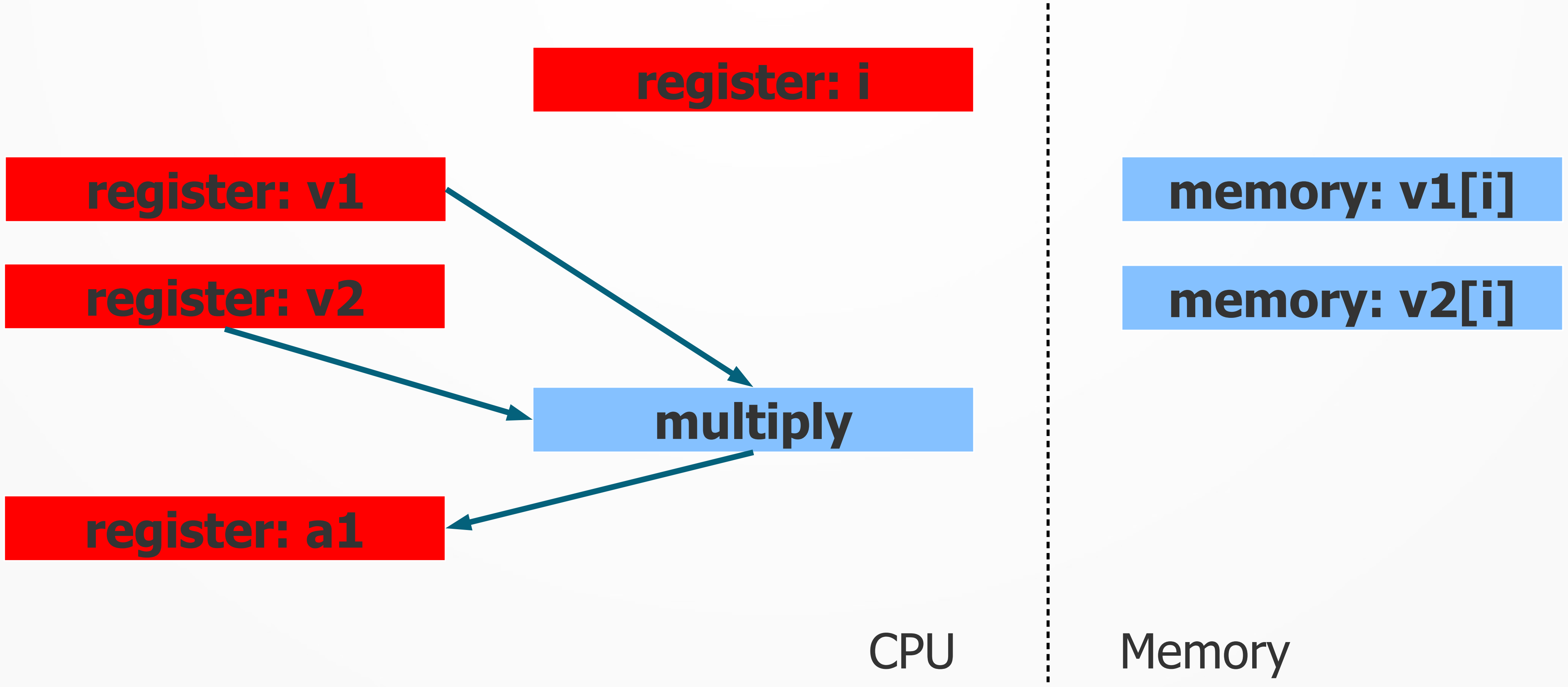
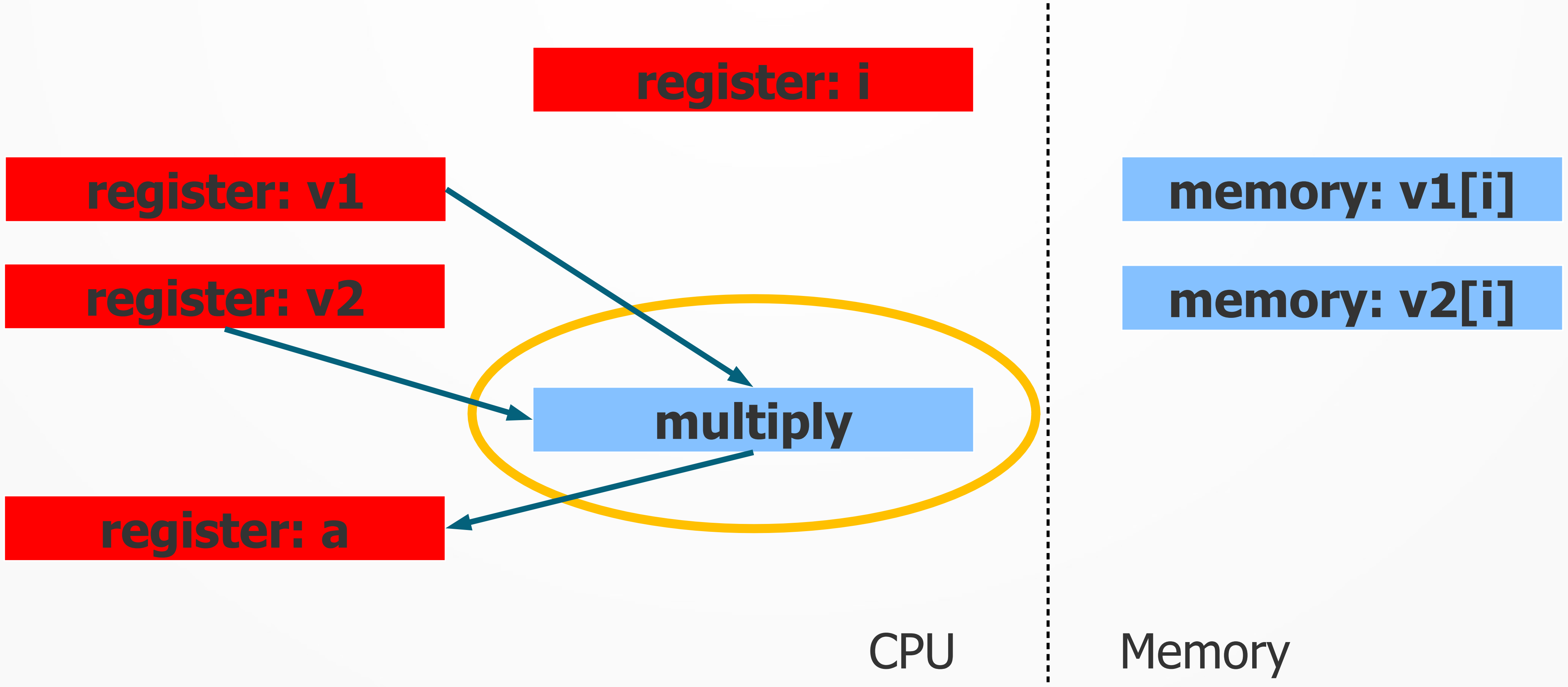
# COMPUTING RESOURCES OF A CPU



# COMPUTING RESOURCES OF A CPU

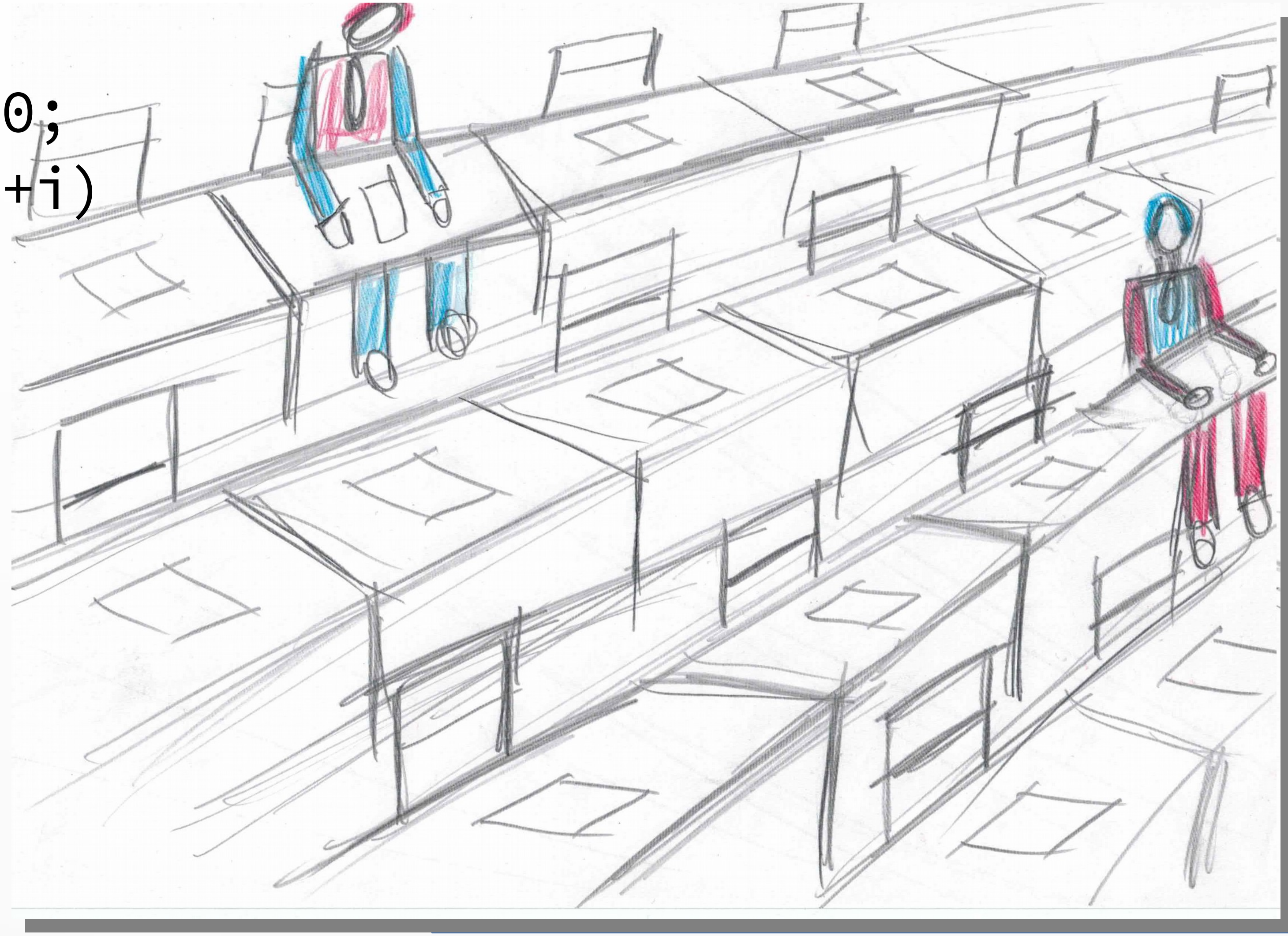


# COMPUTING RESOURCES OF A CPU: USE ALL OF THE HARDWARE



# A LOT OF CPU AREA IS DEDICATED TO COMPUTING. HAS TO BE GOOD FOR SOMETHING?

```
unsigned long v1[N], v2[N];
unsigned long a1 = 0, a2 = 0;
for (size_t i = 0; i < N; ++i)
{
  a1 += v1[i]*v2[i];
  a2 += v1[i]+v2[i];
}
```





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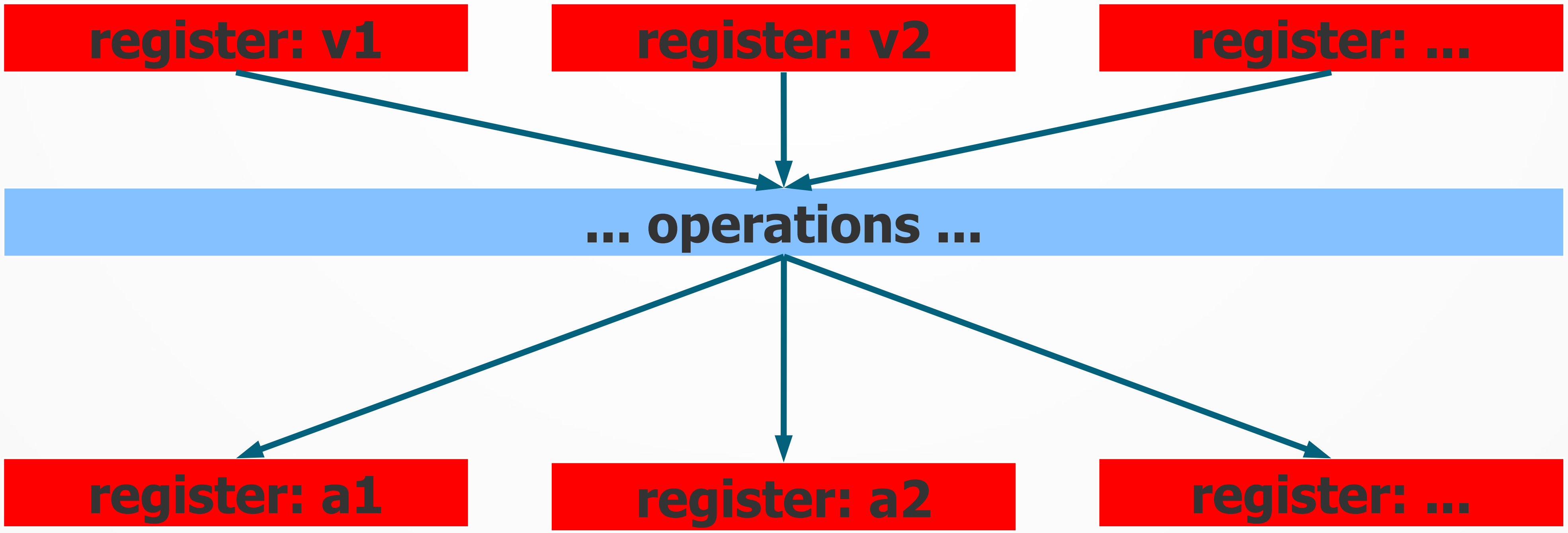
# PROCESSORS CAN DO MULTIPLE OPERATIONS ON MULTIPLE REGISTERS AT ONCE





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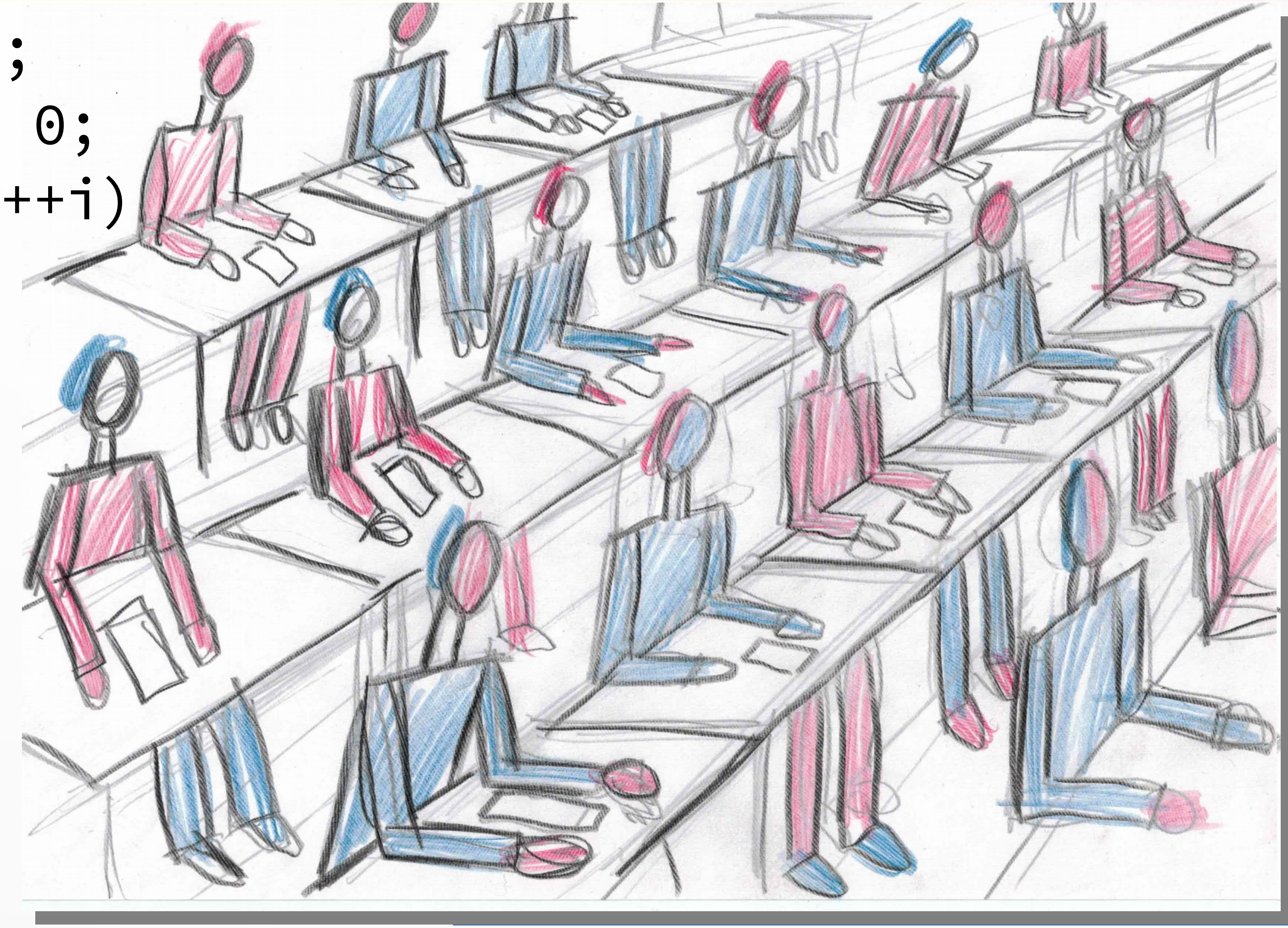
# A LOT OF CPU AREA IS DEDICATED TO COMPUTING. HAS TO BE GOOD FOR SOMETHING?

```
unsigned long v1[N], v2[N];
unsigned long a1 = 0, a2 = 0;
for (size_t i = 0; i < N; ++i)
{
   a1 += v1[i]*v2[i];
   a2 += v1[i]+v2[i];
   ...
}
```





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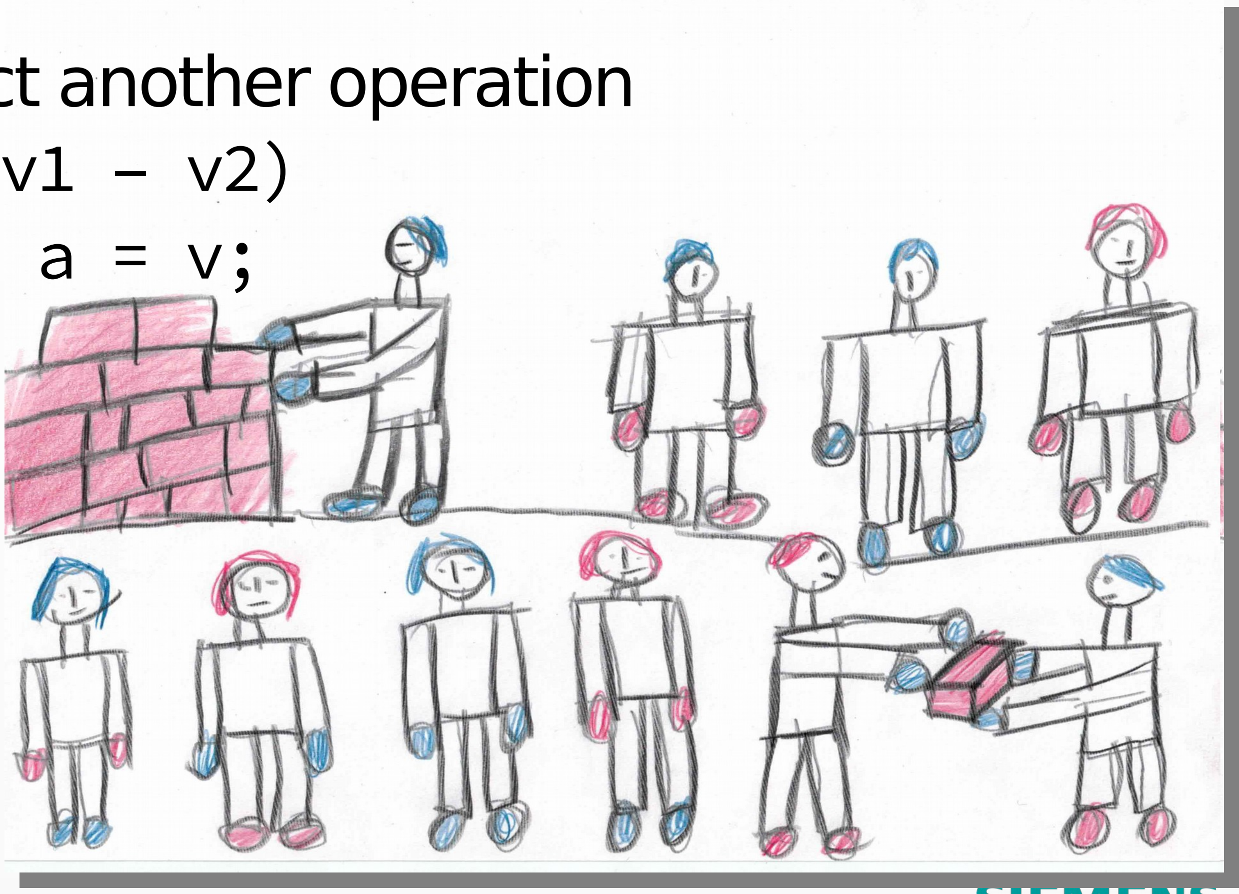
# USE MORE OF THE HARDWARE

- Using multiple compute units is easy when we have multiple independent computations
  - Life is rarely that good
- Usually results of one operation affect another operation
- Data dependency: `a = (v1 + v2)*(v1 – v2)`
- Conditions, or branches: `if (v > a) a = v;`
  - Data-dependent code



# PIPELINING: ANTIDOTE TO DATA DEPENDENCY

- Pipelining is the extension of the ability to execute multiple operations at once:

  `a1 += (v1[i]+v2[i])*(v1[i]-v2[i])`

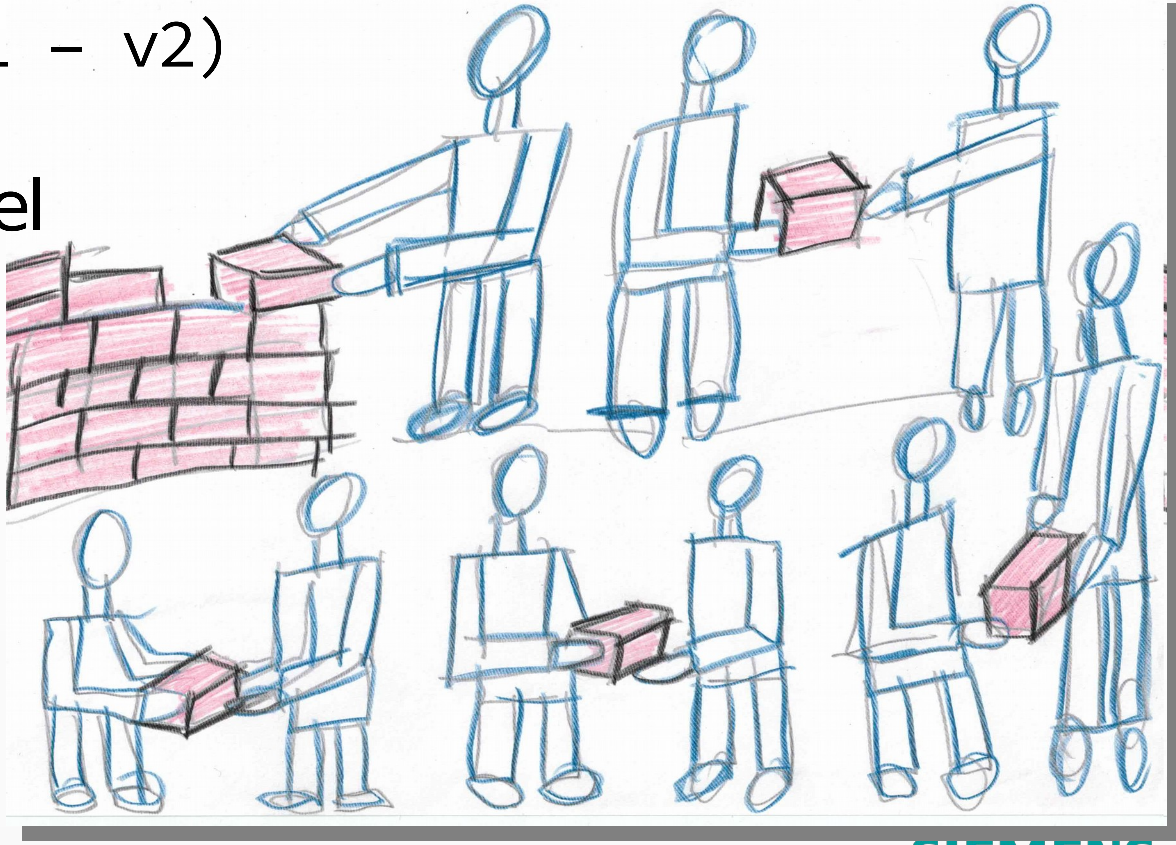
# PIPELINING: ANTIDOTE TO DATA DEPENDENCY

- Pipelining is the extension of the ability to execute operations at once:
  `a += (v1[i]+v2[i])*(v1[i]-v2[i])`

| | | |
|---|---|---|
| s[i-1]:v1[i-1]+v2[i-1] | d[i-1]:v1[i-1]-v2[i-1] | s1[i-2]*d2[i-2] |
| s[i]:v1[i]+v2[i] | d[i]:v1[i]-v2[i] | s1[i-1]*d2[i-1] |
| s[i+1]:v1[i+1]+v2[i+1] | d[i+1]:v1[i+1]-v2[i+1] | s1[i]*d2[i] |

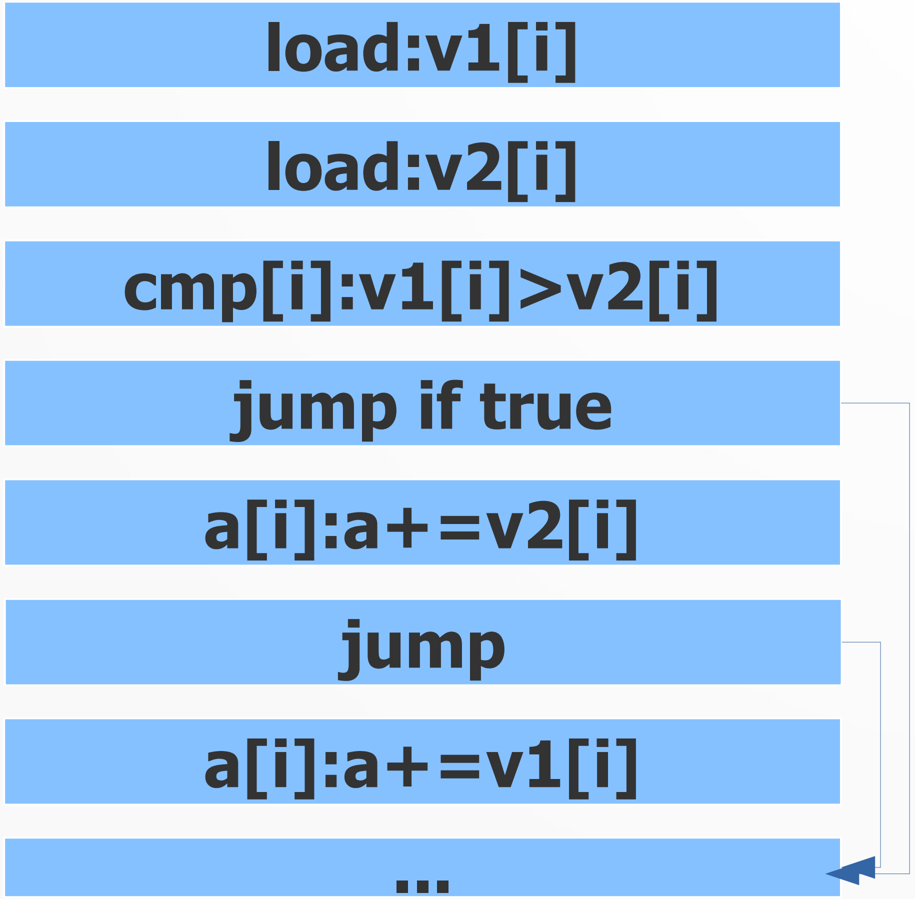
# USE MORE OF THE HARDWARE

- Using multiple compute units is easy when we have multiple independent computations
  - Usually results of one operation affect another operation
- Data dependency: `a = (v1 + v2)*(v1 – v2)`
- Pipeline increases CPU utilization
- Multiple instruction streams run in parallel
  - Dependencies within each stream
  - No data dependencies between streams



# BRANCHES: BANE OF THE PIPELINES

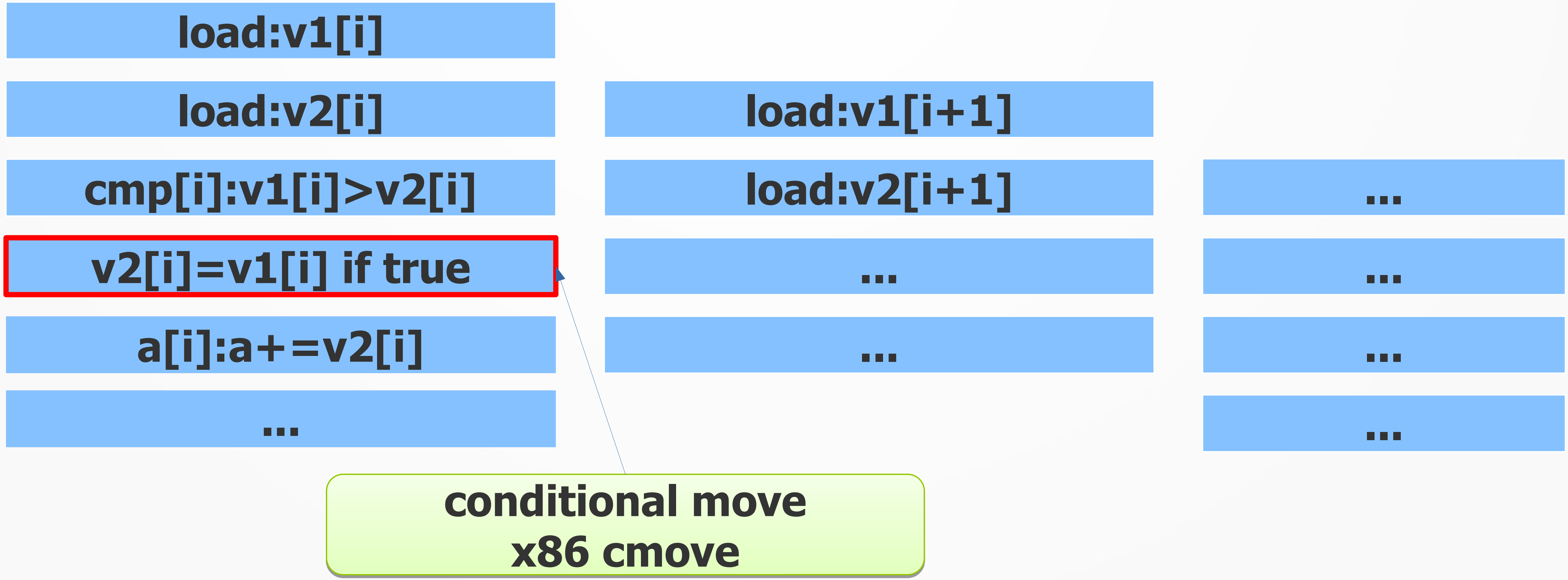
- Hard to pipeline code: `a+=(v1[i]>v2[i])?v1[i]:v2[i]`




- Pipelining relies on a continuous stream of instructions
- Instructions are fetched, decoded, and executed
- Conditional jumps (branches) disrupt that order
- CPU must wait until it knows which instruction to fetch next

# BRANCHES: BANE OF THE PIPELINES

- Not hard to pipeline code: `a+=(v1[i]>v2[i])?v1[i]:v2[i]`



# BRANCHES: BANE OF THE PIPELINES

- Well-pipelined code: `a += v1[i] + v2[i]`

Only if i<N!!!

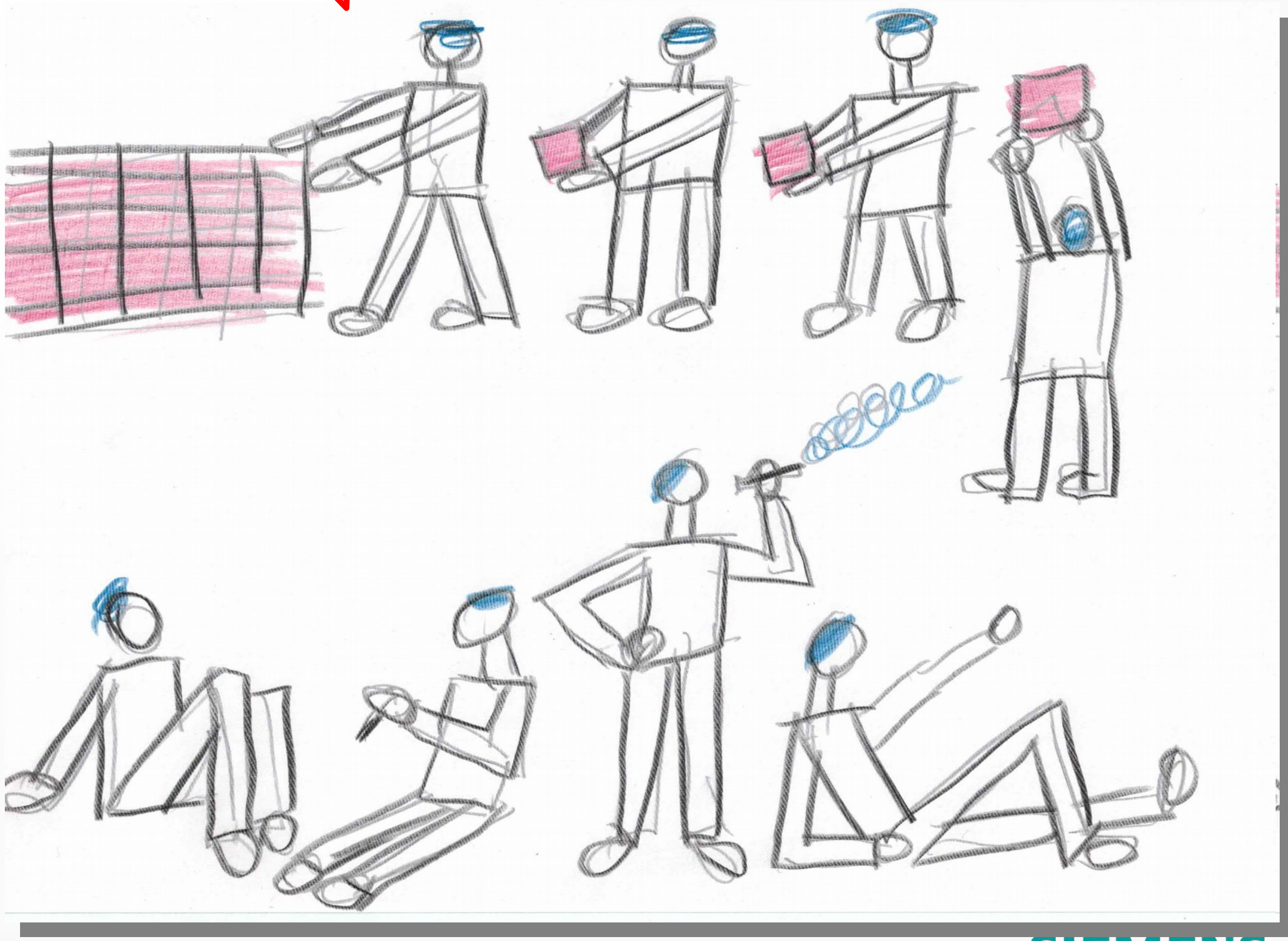
| | | |
|---|---|---|
| load:v1[i] | | |
| load:v2[i] | load:v1[i+1] | |
| s[i]:v1[i]+v2[i] | load:v2[i+1] | v1[i+2]: |
| a[i]:a+=s[i] | s[i+1]:v1[i+1]+v2[i+1] | v2[i+2]: |
| load:v1[i+w] | a[i+1]:a+=s[i+1] | s[i+2]: |
| | | a[i+2]: |

- Cannot run the pipeline for i+2 before checking that i+2<N!

# BRANCH PREDICTION: ANTIDOTE TO BRANCHES

- Well-pipelined code: `a += v1[i] + v2[i]`
- CPUs have branch predictors

**Usually i<N**



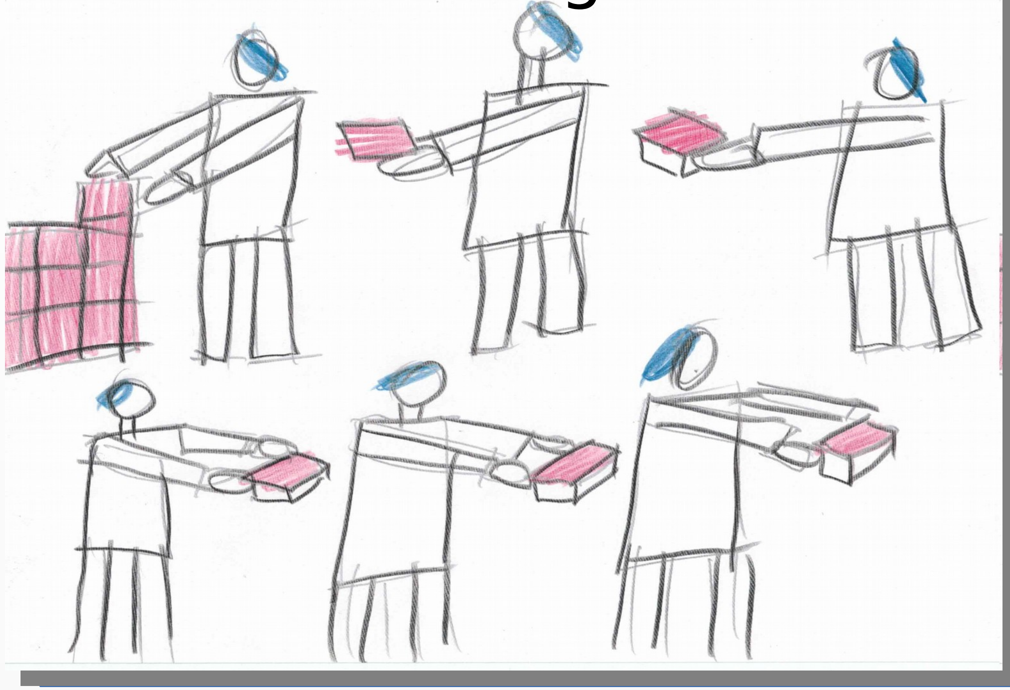
# LOOP UNROLLING

```
for (size_t i = 0; i < N; ++i) {
    a += v1[i]+v2[i];
}
```

- CPU immediately goes to the next iteration without waiting for i<N

```
a += v1[1]+v2[1];
a += v1[2]+v2[2];
a += v1[3]+v2[3];
...
```

- Successive iterations are pipelined
- Hardware loop unrolling

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# LOOP UNROLLING – HOW?

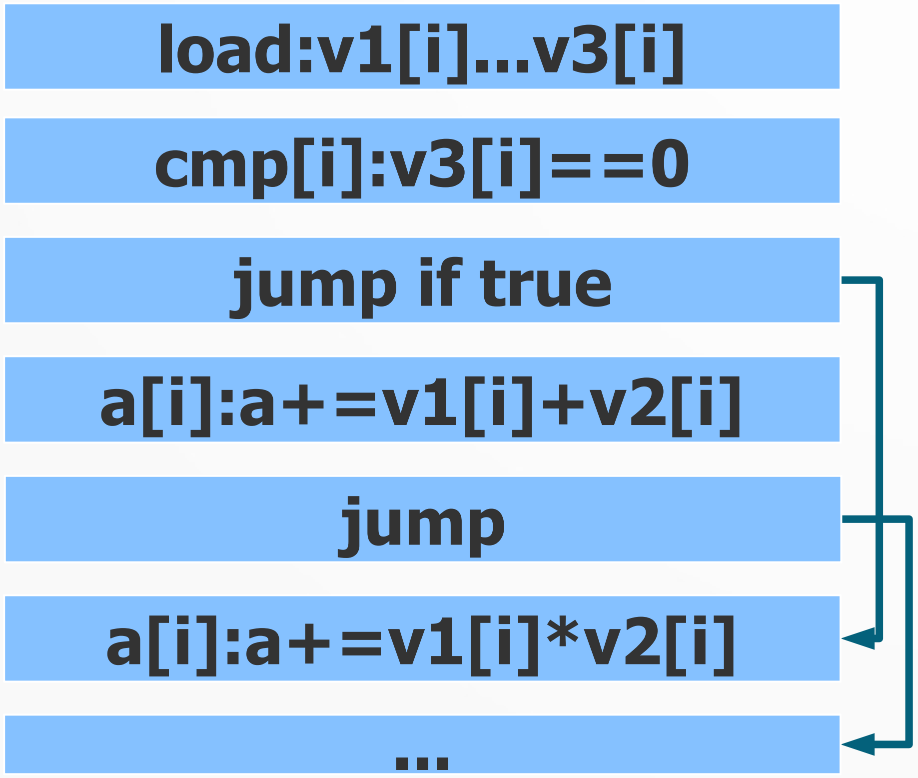
- Machine code does not show any unrolling

```
for (size_t i = 0; i < N; ++i) {
    a += v1[i]+v2[i];
}
```

- How can next stage of the pipeline run if registers are still in use?
- Register renaming: “rcx” does not mean “rcx”, CPUs have a lot more physical registers that are aliased to architecture register names like “eax” or “rcx”
- Result is hardware loop unrolling
  - Also out of order execution (data hazard)

# BRANCHES: BANE OF THE PIPELINES

- Hard to pipeline code: a += (v3[i]) ? (v1[i]+v2[i]) : (v1[i]*v2[i])

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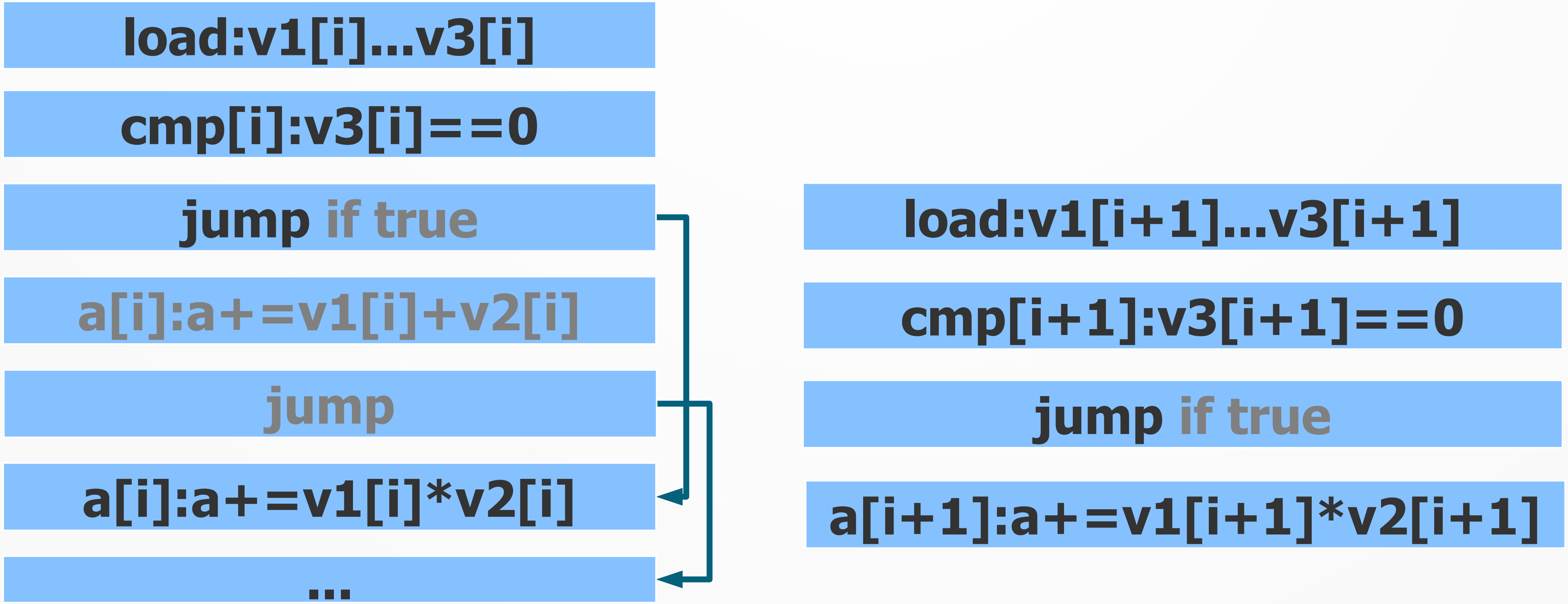
# BRANCH PREDICTION: ANTIDOTE TO BRANCHES

- Speculatively pipelined code: a += (v3[i]) ? (v1[i]+v2[i]) : (v1[i]*v2[i])



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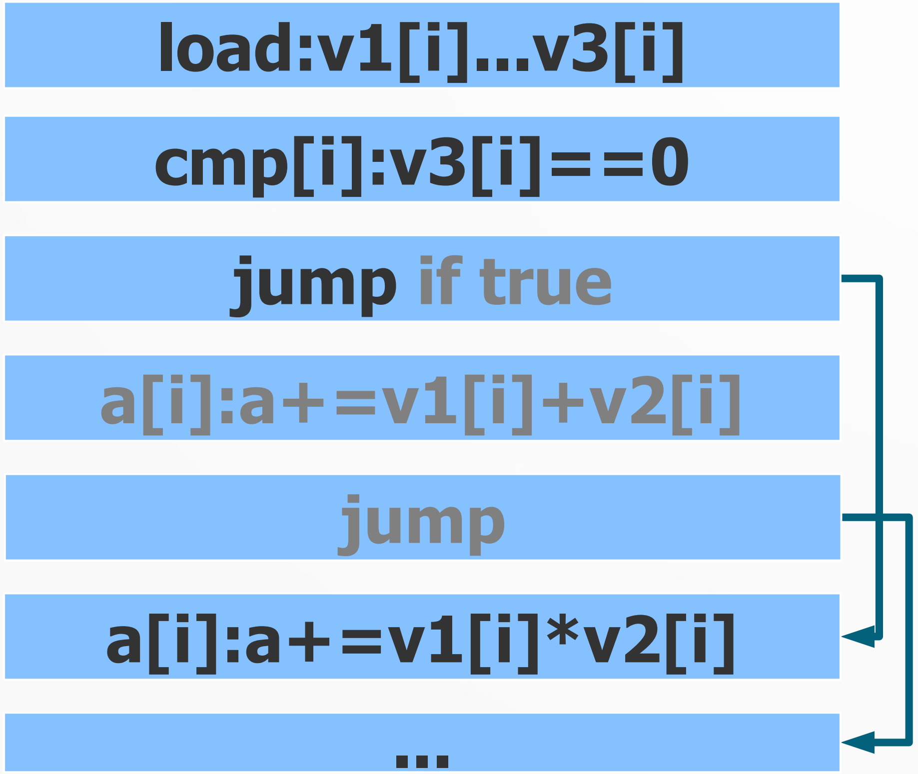
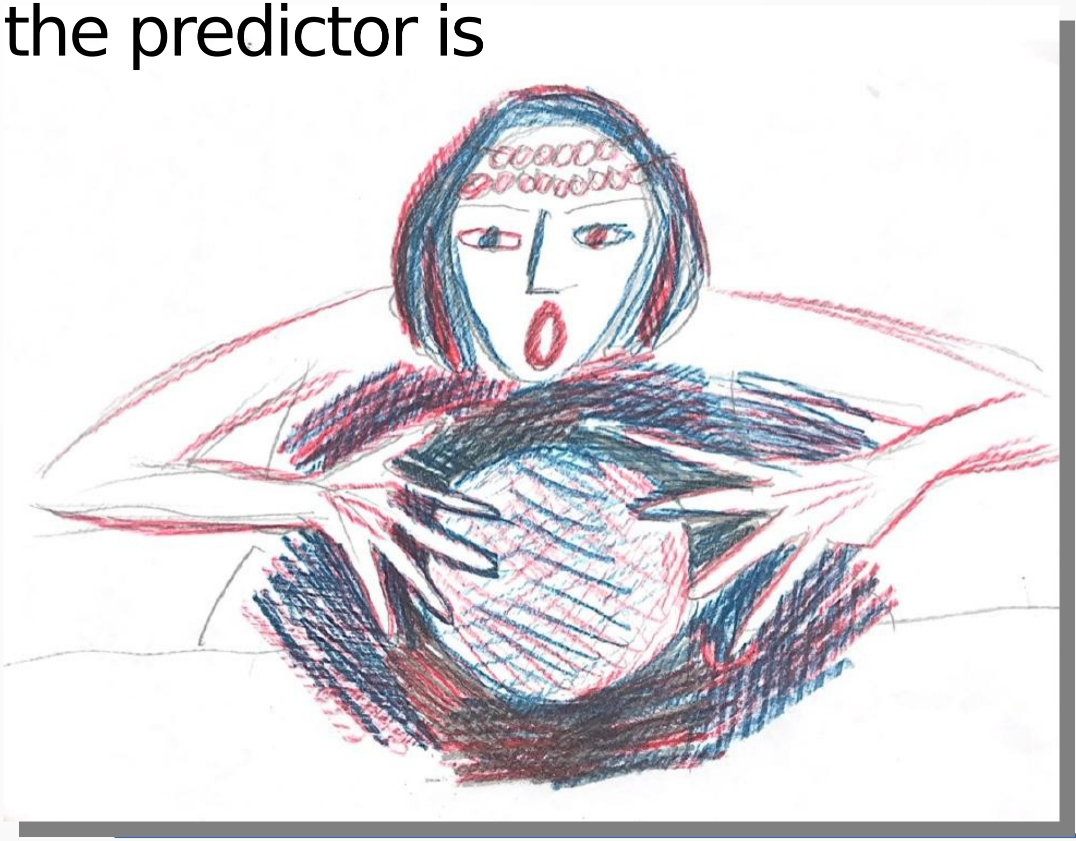



- Performance critically depends on how effective the predictor is





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# BRANCH PREDICTION: ANTIDOTE TO BRANCHES

- Well-pipelined code: `a += v1[i] + v2[i]` ← **Usually i<N**
- CPUs have branch predictors
- Branch predictors are associative caches, they remember the outcome of the conditional for the same place in the code
- CPU assumes that the same branch will be taken (i<N) and proceeds to pipeline and evaluate instructions
- Actual result of the conditional becomes known several cycles later
- If the prediction was correct, nothing else needs to happen
- If the prediction was wrong…

# BRANCH MISPREDICTIONS

- If branch prediction was wrong, several things need to happen:
- All predicted computations are discarded or aborted
  - Pipeline flush
- New computations have to be started
- Any results of mispredicted computations have to be undone
  - Anything that cannot be undone cannot be done speculatively



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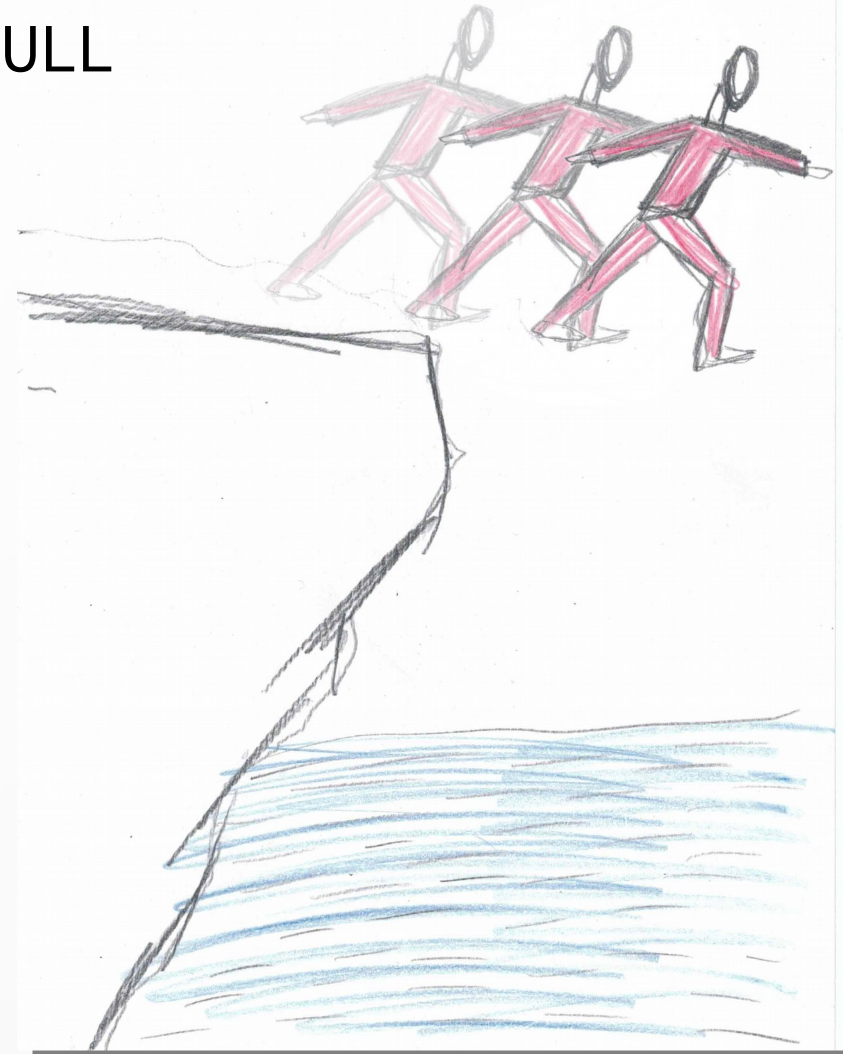
# BRANCH MISPREDICTIONS AND ERRORS

```
if (p != NULL) *p = 1;          // p is rarely NULL
int v[N];
for (size_t i=0; i<N; ++i) {
    v[i]=i;                      // Usually i<N
}
```





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int v[N];
for (size_t i=0; i<N; ++i) {
    v[i]=i;                   // Usually i<N
}
```

- Any errors are held until branch is evaluated
- Errors that do not actually happen must not be reported
- Memory writes must be held (destination may not be accessible)

# BRANCH PREDICTION: ANTIDOTE TO BRANCHES

- Well-pipelined code: `a += v1[i] + v2[i]`

Usually i<N

| | | |
|---|---|---|
| load:v1[i] | | |
| load:v2[i] | load:v1[i+1] | |
| s[i]:v1[i]+v2[i] | load:v2[i+1] | v1[i+2]: |
| a[i]:a+=s[i] | s[i+1]:v1[i+1]+v2[i+1] | v2[i+2]: |
| load:v1[i+w] | a[i+1]:a+=s[i+1] | s[i+2]: |
| | | a[i+2]: |

- Branch misprediction and pipeline flush at the end of the loop
- Branch predictor is effective – pipelining works – CPU utilization is good

# CODE

```
v1 = ... some data ...;
v2 = ... some data ...;
v3[i] = 0;
//v3[i] = 1;
//v3[i] = rand();
for (size_t i = 0; i < N; ++i) {
    if (v3[i]) a1 += v1[i]+v2[i];
    else a2 += v1[i]*v2[i];
}
```

# RESOURCES

- Google Benchmark:
  - https://github.com/google/benchmark
- Perf:
  - Usually part of Linux distribution
  - https://perf.wiki.kernel.org/index.php/Main_Page
  - Manual install involves compiling the kernel


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# BENCHMARK

- 01a
- 01b
- with perf

# BRANCH MISPREDICTION IS VERY EXPENSIVE

- v3[i] = 0:
  perf stat ./branch_predictions
  0.05% branch misses
- v3[i] = rand():
  perf stat ./branch_predictions
  10% branch misses

5x slower

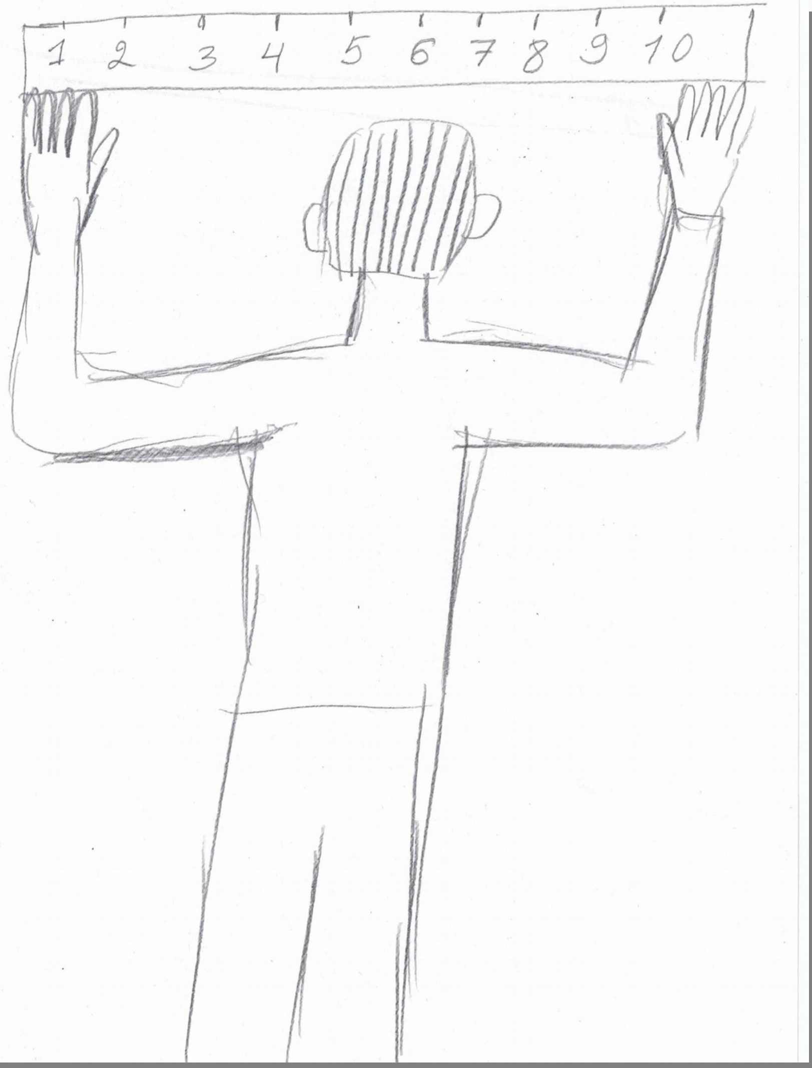
- Optimizations to eliminate conditionals are usually invasive and may use more memory
- Branch predictors are quite complex
- Do not optimize until misprediction is confirmed by a profiler

# BENCHMARK

- 01c
- with perf

# BRANCH MISPREDICTION IS VERY EXPENSIVE

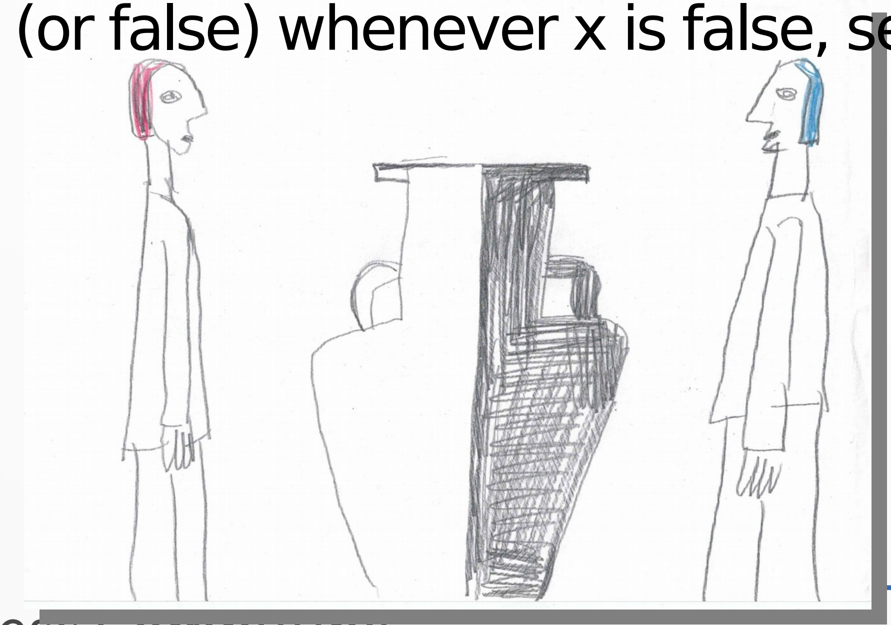
- Optimizations to eliminate conditionals usually are invasive and may use more memory
- Branch predictors are quite complex
  - Patterns in branch conditions are recognized
  - Differences in call stacks are detected
- **Do not optimize until misprediction is confirmed by a profiler**



# WHAT IS A BRANCH?

```
if (x || y) do_it(); else dont_do_it();
```

- Programmer's view:
  - if we always do it, branch is predictable
- Processor's view:
  - if x is always true (or false), first branch is predictable
  - if y is always true (or false) whenever x is false, second branch is predictable

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- Programmer's view:
  - if we always do it, branch is predictable
- Processor's view:
  - if x is always true (or false), first branch is predictable
  - if y is always true (or false) whenever x is false, second branch is predictable
- Root of the difference: Boolean expression evaluation is short-circuited
  - Evaluation must stop when the result is known
  - Important: if (*a || *b) … - b may be null whenever *a is true
- May be very expensive if the Boolean expression is complex, terms vary, but the overall result is predictable

# BENCHMARK

- 02a
- with perf

# OPTIMIZING FALSE BRANCH

```
if (x || y) do_it(); else dont_do_it();
```

- x may be true or false
- y may be true or false
- x || y is usually true
- Temporary variable:

```
bool cond = x || y; if (cond) ...
```

  - Does not work at all:
  - compiler will get rid of it
  - it’s still two branches

# OPTIMIZING FALSE BRANCH

```
if (x || y) do_it(); else dont_do_it();
```

- x may be true or false
- y may be true or false
- x || y is usually true
- Integer or bitwise arithmetic on **bool**:

```
if (bool(x) + bool(y)) ... or if (bool(x) | bool(y)) ...
```

  - Works great unless the compiler “optimizes” operator + to ||
  - Some compilers do this (often for + or | but not both), some don’t
  - Profiling and/or examining assembly output is necessary

# BENCHMARK

- 02b, 02c
- with perf

# BRANCHES ARE THERE TO AVOID UNNECESSARY WORK

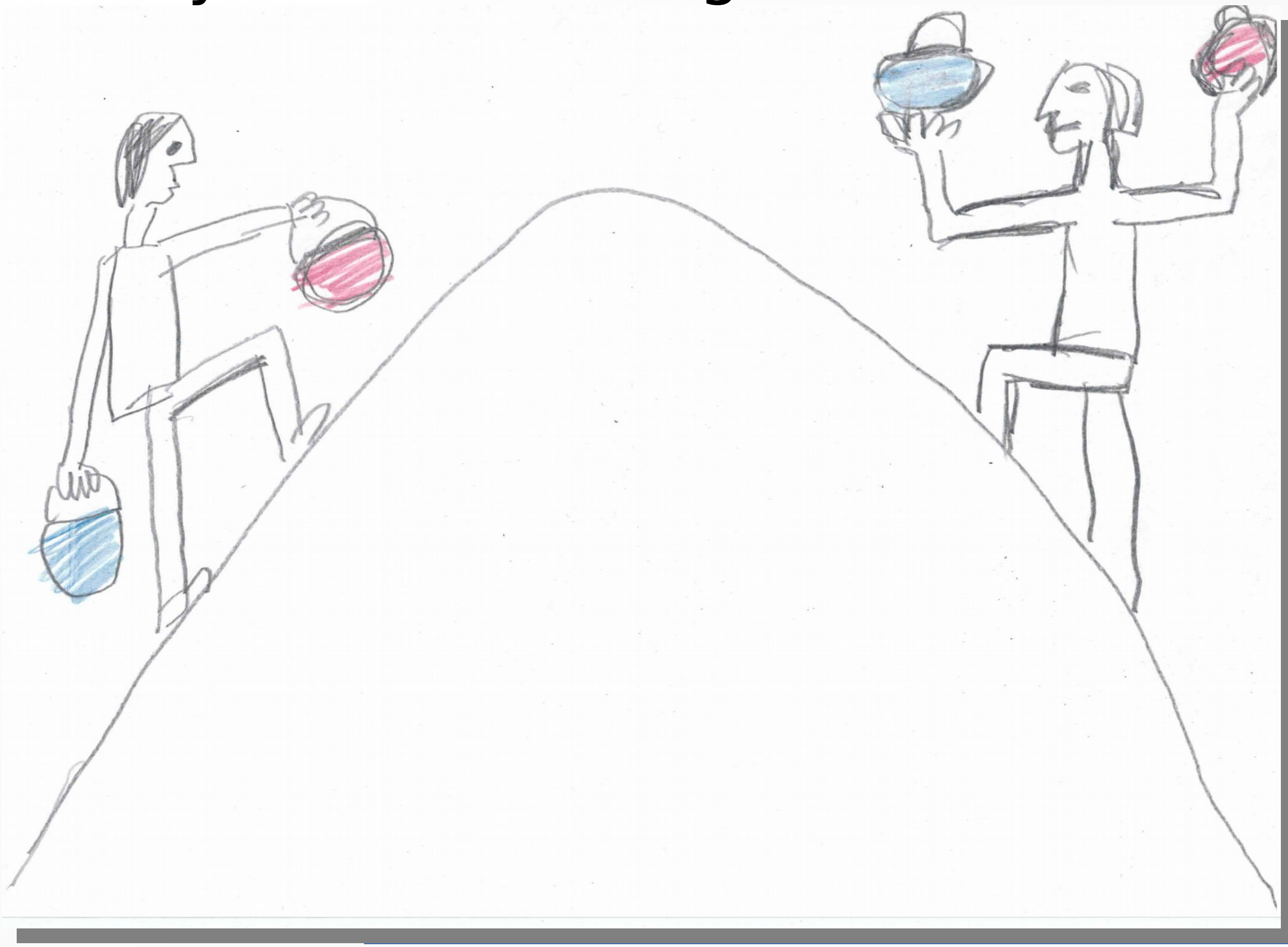
- Optimizing away branches almost always results in doing more work!

```
if (x + y) ...
```

- Always evaluates x and y
- Always evaluates the sum

```
if (x || y) ...
```

- Always evaluates x, maybe y
- Does not evaluate || if x is true
- || is less work





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# BRANCHES ARE THERE TO AVOID UNNECESSARY WORK

- Optimizing away branches almost always results in doing more work!
- CPU usually has idle compute resources – can handle a bit of extra work
- Branch misprediction is very expensive
  - Predicted branch is just another instruction
- Tradeoff between the extra work vs the cost of the branch is usually impossible to predict – it must be measured

# IF ONE BRANCH IS BETTER THAN TWO, THEN ZERO BRANCHES IS BETTER THAN ONE

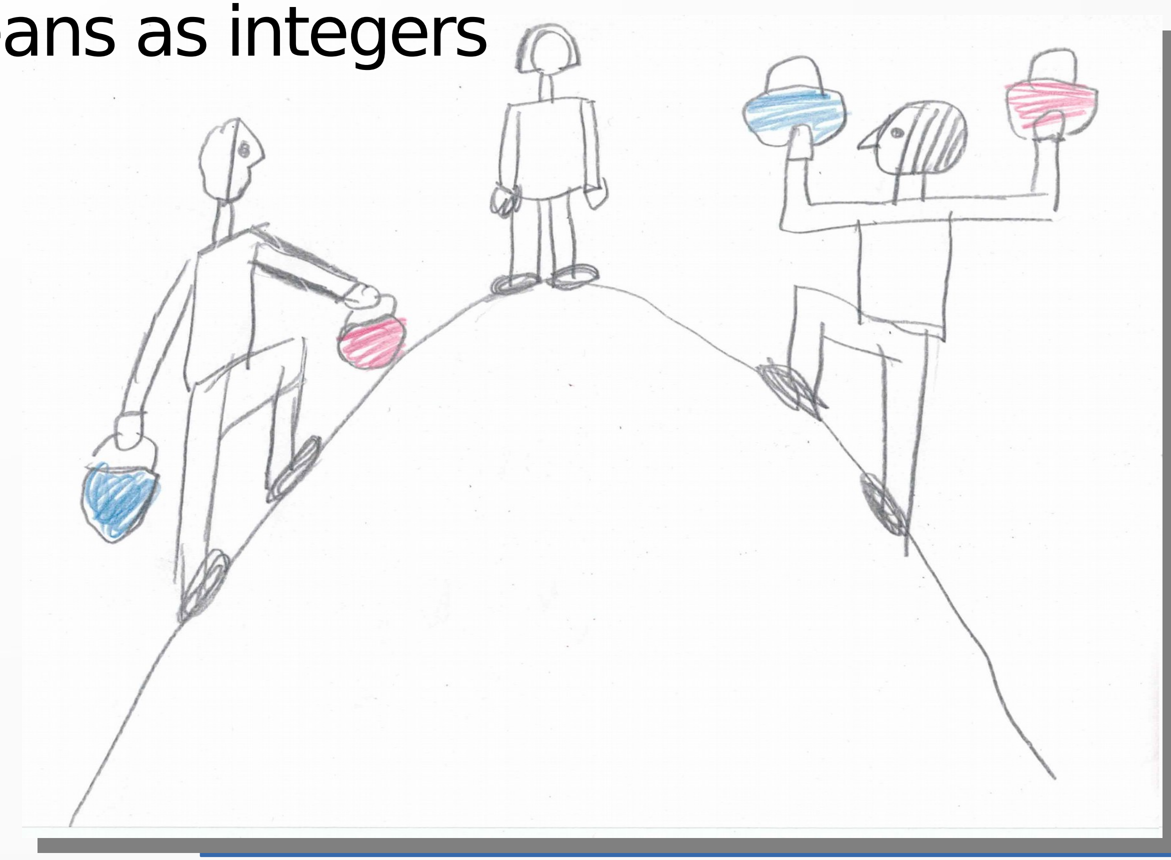
- Branchless computing – eliminate branches completely, but how?

```
sum += cond ? expr1 : expr2;
```

- Branchless implementation uses Booleans as integers

```
term[2] = { expr2, expr1 };
sum += term[bool(cond)];
```

- Both expressions are evaluated
- Improves performance if:
  - extra computations are small
  - branch is poorly predicted





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# BENCHMARK

- 03a, b – branch is not predicted, optimization works
- 03c, d – branch is well-predicted, no optimization

# ADVANCED OPTIMIZATION – ALWAYS MEASURE

- Sometimes the compiler will do a branchless transformation for you
  - Often using “conditional move” instructions (they are not branches)
- Compiler’s branchless optimization is usually better than yours
- In particular, this is almost always branchless in reality:

```
return cond ? x : y;
```

- Never optimize such code preemptively
- Optimize only if the profiler shows high misprediction rate
- Optimizations depend on the compiler!



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# BENCHMARK

- 04c, d – optimization does not work with GCC
- with perf – no branch




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# ADVANCED OPTIMIZATION – ALWAYS MEASURE

- Sometimes the compiler will not do a branchless transformation for you
- This is almost always branchless in reality:

```
return cond ? x : y;
```

- But very similar code may not be
- Never optimize such code preemptively
- Optimize only if the profiler shows high misprediction rate

# BENCHMARK

- 05a, b – optimization does work
- with perf – bad branch

# ADVANCED OPTIMIZATION – ALWAYS MEASURE

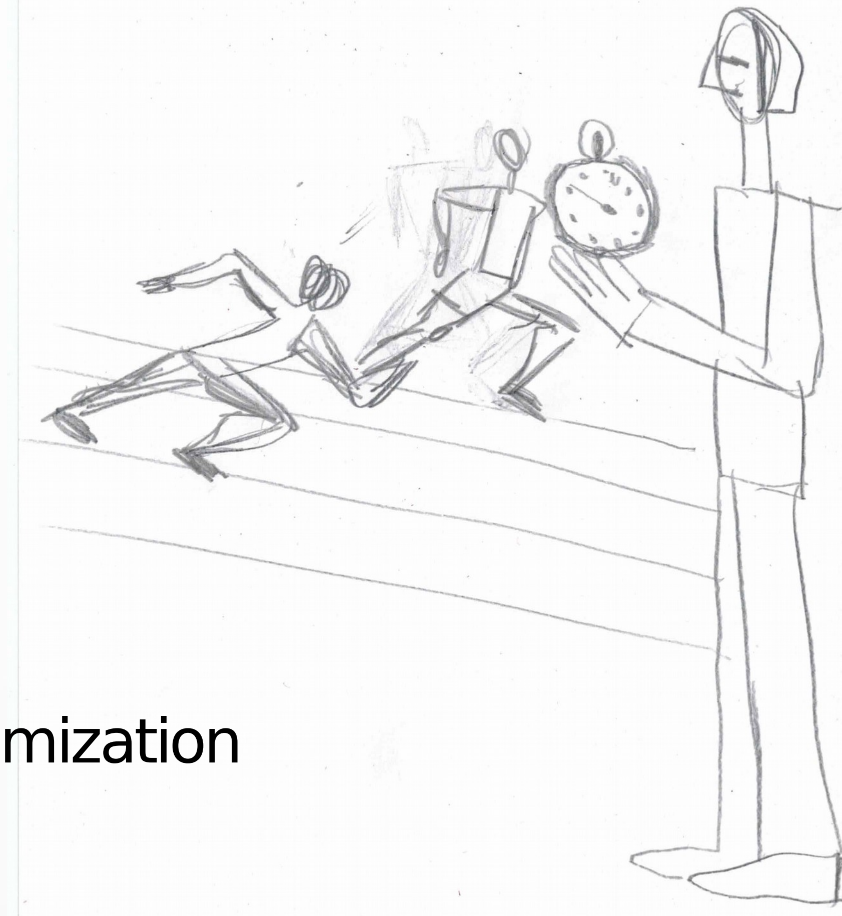
- Sometimes branchless code is not really branchless
- Indirect function calls are similar to branches

```
if (cond) f1(); else f2();
```

- Can be converted to branchless:

```
funcptr f[2] = { &f2, &f1 };
(f[cond])();
```

- This "optimization" almost never works
  - If f1() and/or f2() were inlined, it's a spectacular pessimization
- Be careful – always measure





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# BENCHMARK

- 06a, b – optimization does not work
- with perf – bad branch either way

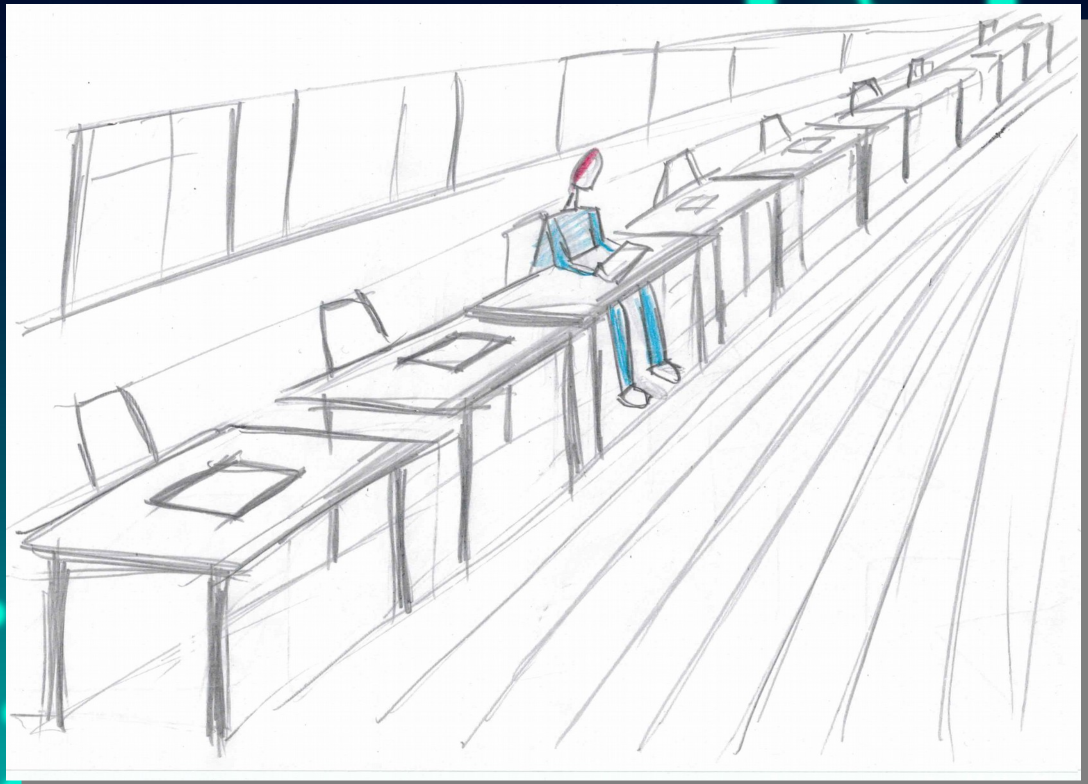
# SUMMARY

- For best performance, use the hardware efficiently
- Use all of the hardware all the time (ideal goal)
- Processors can do many computations at once every cycle
- Limiting factor is usually availability of data
- Workaround is pipelining – running multiple instruction streams at once
- Limiting factor is conditional code – next instruction is data-dependent
- Workaround is branch prediction – guess the next instruction and go on
- Limiting factor is the ability to guess the future
- Workaround is writing unconditional code with data dependencies

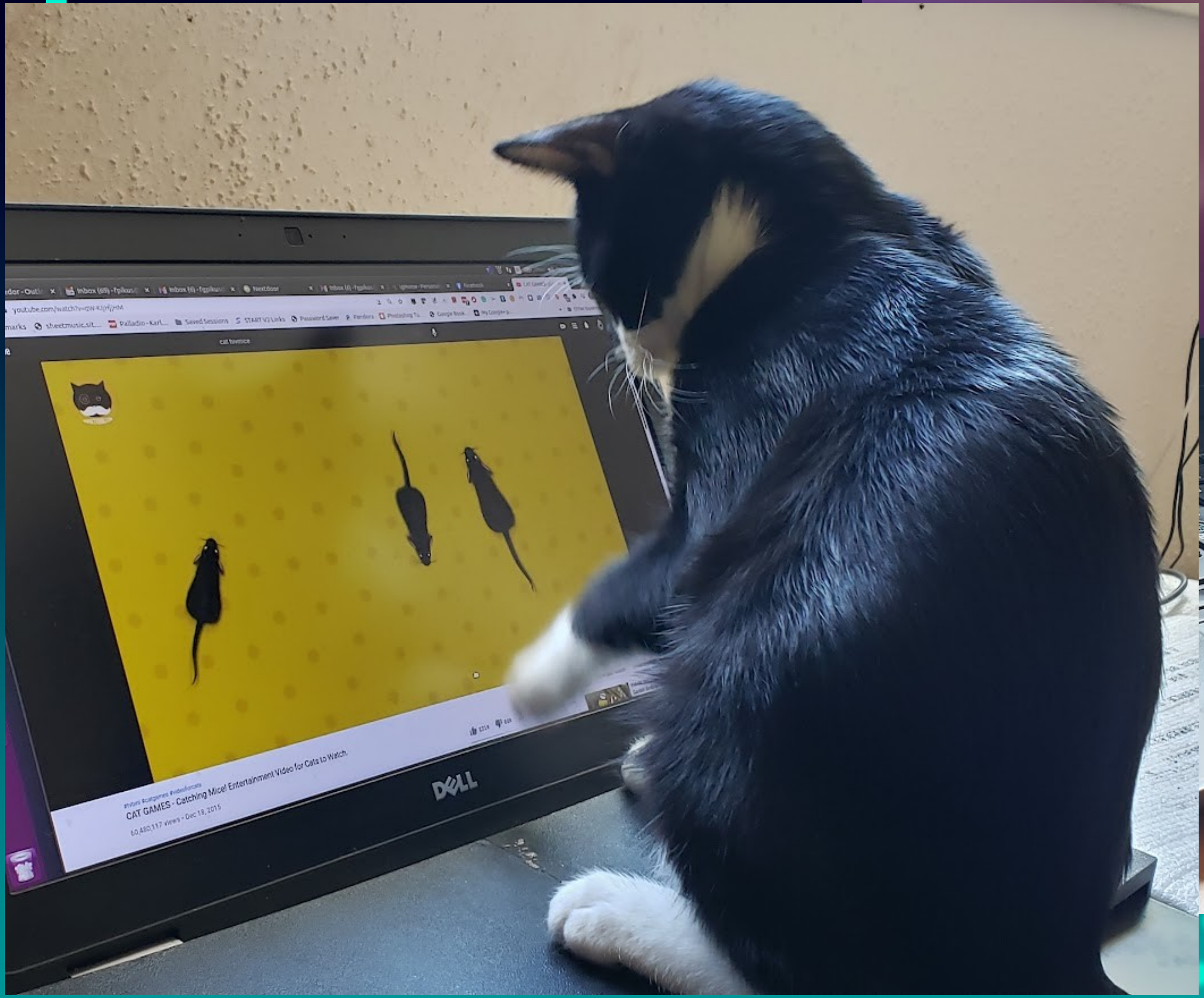
# LESSONS LEARNED

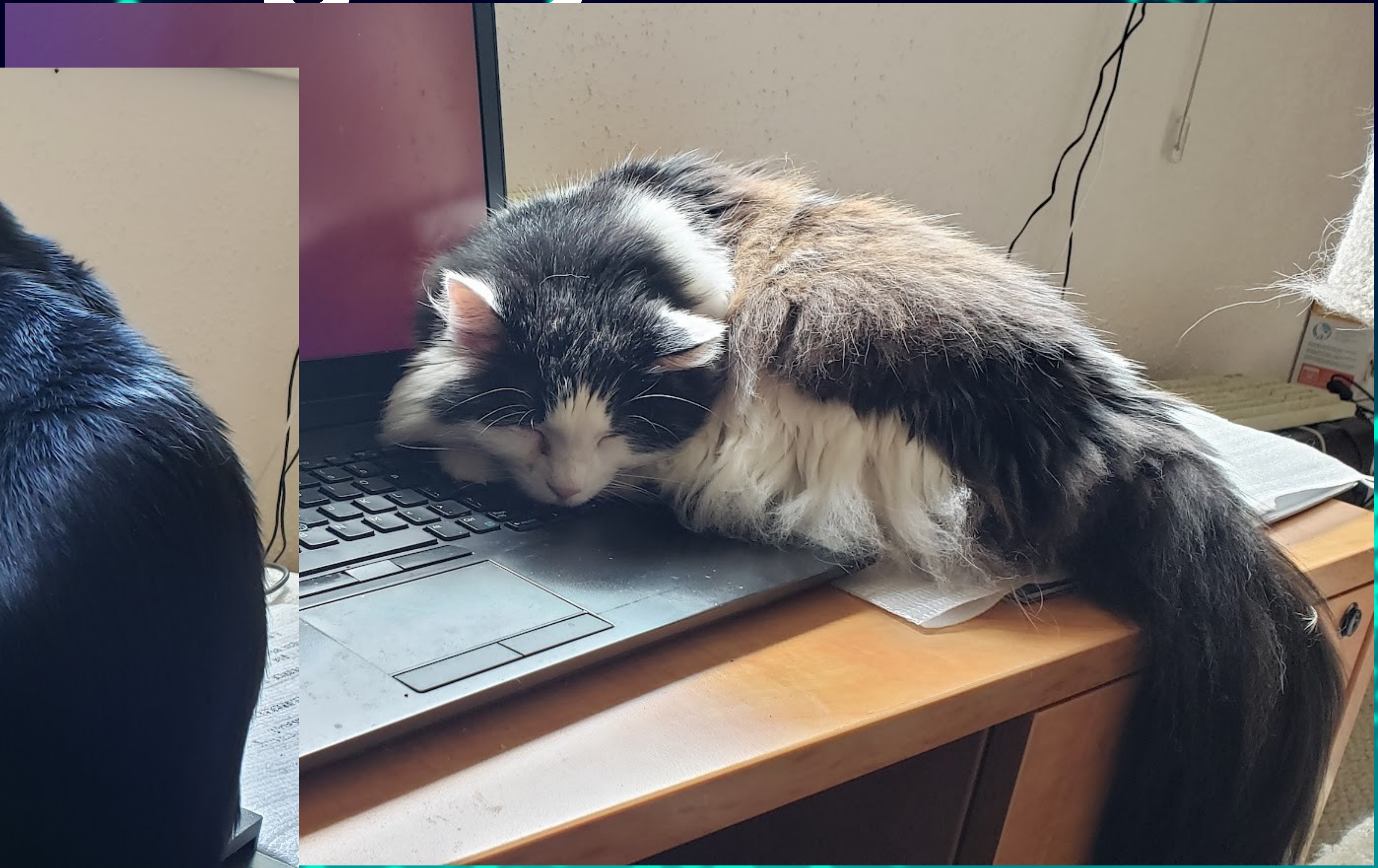
- Predicted branches are cheap
- Mispredicted branches are very expensive – pipeline flush
- Optimization – use fewer (or zero!) branches
- Always use profiler to detect and validate optimization locations
- Don’t fight with the compiler – sometimes it does the job for you

# Illustrations by Evgenia Golant



# PC Sharing by



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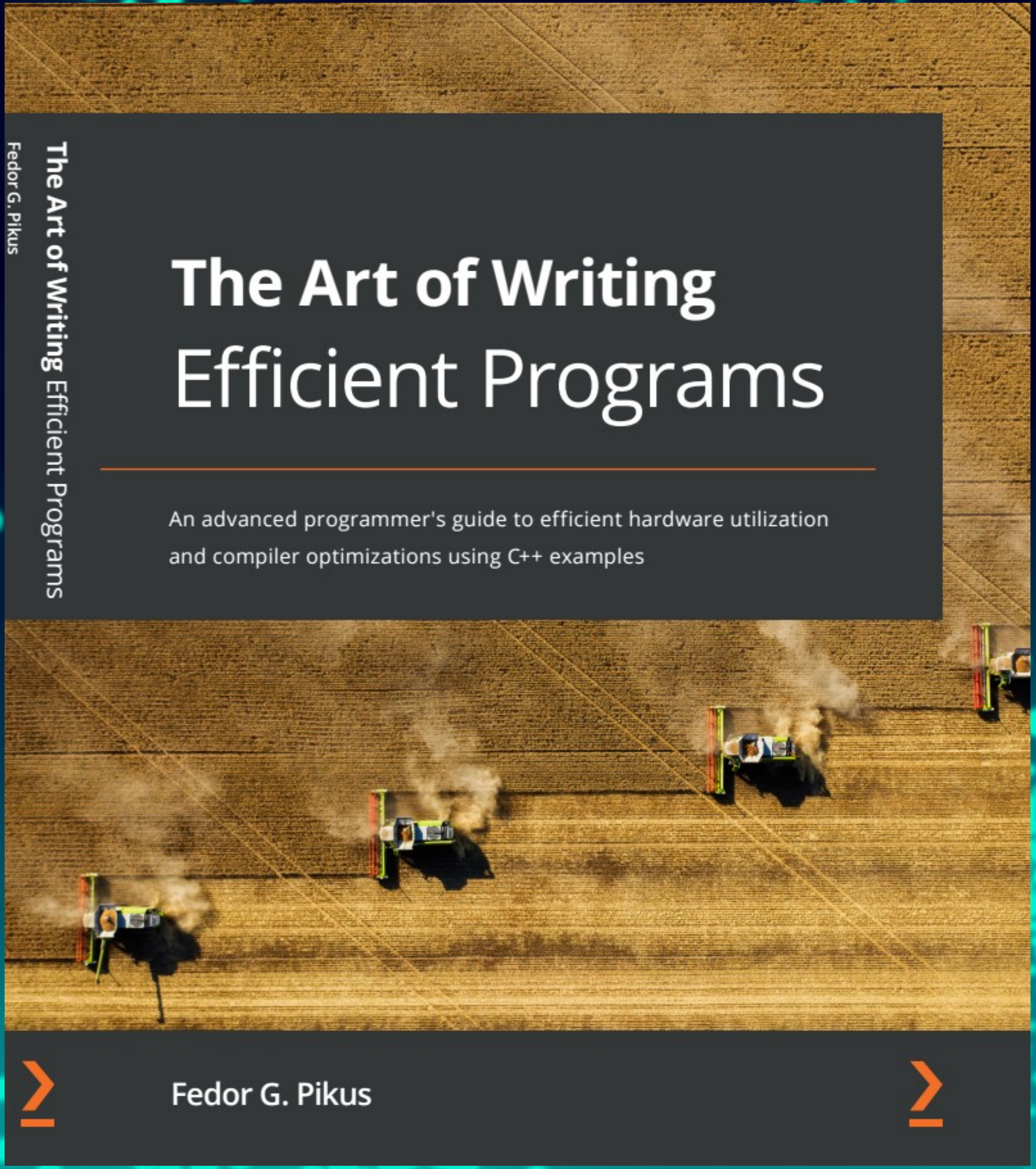
# Questions?

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