Optimization
Branches

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"Foundation of HPC - basic" course

DATA SCIENCE &
SCIENTIFIC COMPUTING

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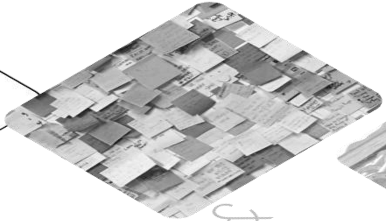
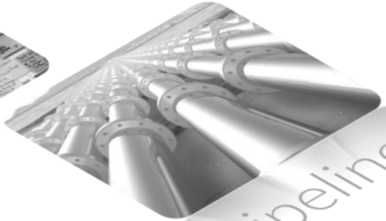
Outline

First things first

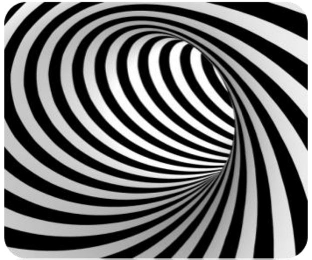


Cache & Memory



Pipelines

Branches



Loops

Outline

a) Definition of conditional branches

b) Data-dependent execution flow

c) Data-dependent data flow

d) impact of conditional branches on the code efficiency

e) 4 examples about hot to clean/restructure a code
   1. conditional branches inside loops
   2. unpredictable data streams
   3. sorting two arrays
   4. filling a matrix

| Don’t loose control

Whenever either *(i)* the sequence of operations that must be executed or *(ii)* the sequence of data to be processed depends on some condition, i.e. on the outcome of a test performed on some data or result, we have a *conditional execution*.

Modern architecture offer 2 distinct low-level instructions to implement a conditional execution upon a test:

- modifying the *control flow* → data-dependent execution-flow
- modifying the *data flow* → data-dependent data-flow

Low-level control

Let's see the conditional execution flow as first.

At machine level, the way to alter the execution flow is through a **jump instruction**, that causes the control to be passed to a different code section.

The jump instruction can be *conditional*, when its execution depends on the outcome of some operation (a test), or *unconditional* if it is not.

A function call is a jump instruction of particular type, in which we are not interested here.

Low-level control

`jmp` is the only *unconditional* instruction; it accepts either a *direct* destination (specified by a label) or an *indirect* destination (specified through an address in a register or in memory).

`je`, **`jne`** and the others, are *conditional* instructions: i.e. their execution depends on a condition.
These instructions access the values stored in the bits of the flag register, a special register where the CPU inscribes some characteristics outcomes of the last arithmetic or logical operation

`CF`	CARRY FLAG; a carry out of the msb has been generated, signaling an overflow in unsigned op
`ZF`	ZERO FLAG; the most recent op resulted in a zero
`SF`	SIGN FLAG; the most recent operation ended in a negative result
`DF`	OVERFLOW FLAG; a two's-complement overflow, either negative or positive.

This table shows some of the low-level jump instructions routinely available on modern CPUs.

`jmp`	*Label* **Operand*	direct jump indirect jump
`je`	*Label*	jump if equal / zero
`jne`	*Label*	jump if not equal / zero
`js`	*Label*	jump if negative
`jns`	*Label*	jump if not negative
`jg`	*Label*	jump if greater
`jge`	*Label*	jump if greater or equal
`jl`	*Label*	jump if less
…	…	…

Low-level example: for loop

Let's inspect how simple for cycle translates in assembler:

```c
for ( int i = 0; i < 10; i++ )
  array[i] = 0;
```

```asm
.L2:
        mov     DWORD PTR [rax], 0
        add     rax, 4
        cmp     rax, rbp
        jne     .L2
```

`AX` contains the address of `array`

Direct memory access at *i*-th element of `array`

The address to be referenced is increased (equivalent to increase the counter `i`)

The comparison operator; it amounts to `rax-rbp` and sets the flag `ZF` (note: `rbp` contains the termination value)

`jump if not equal`, i.e. jumps to .L2 if the `ZF` flag is not set

Low-level example: for loop

This is the linear flow of execution in the cycle body

```
.L2:
        mov     DWORD PTR [rax],
        add     rax, 4
        cmp     rax, rbp
        jne     .L2
```

Until `rax <= rbp` (i.e. `i < 10`) there is a *backward jump* and the body is executed again.

When the jump is *not* executed and the control flow continues afterwards.

Low-level example: if statement

```c
if ( a < b )
  c = a+b;
else
  c = a-b;
```

```asm
        mov     eax, DWORD PTR -8[rbp]
        cmp     eax, DWORD PTR -4[rbp]
        jge     .L2
        mov     edx, DWORD PTR -8[rbp]
        mov     eax, DWORD PTR -4[rbp]
        add     eax, edx
        mov     DWORD PTR -12[rbp], eax
        jmp     .L3
.L2:
        mov     eax, DWORD PTR -8[rbp]
        sub     eax, DWORD PTR -4[rbp]
        mov     DWORD PTR -12[rbp], eax
.L3:
```

Note: compiled without optimization, though

Low-level example: if statement

move a in `AX`

cmp a with b
(amounts to `a-b`)

check `ZF` and `SF`
(zero and sign flag)

```
if ( a < b )
   c = a+b;
else
   c = a-b;
```

```
        mov     eax, DWORD PTR -8[rbp]
        cmp     eax, DWORD PTR -4[rbp]
        jge     .L2
        mov     edx, DWORD PTR -8[rbp]
        mov     eax, DWORD PTR -4[rbp]
        add     eax, edx
        mov     DWORD PTR -12[rbp], eax
        jmp     .L3
.L2:
        mov     eax, DWORD PTR -8[rbp]
        sub     eax, DWORD PTR -4[rbp]
        mov     DWORD PTR -12[rbp], eax
.L3:
```

Jump if
`a > b`

Unconditional jump after the branch `a < b`

Low-level example: if statement

Note:

The **`true`** branch is the closest to the test condition, while the **`false`** branch is reached upon a jump.

→ when coding, if possible pay attention to what is most likely to be true, to preserve the code locality.
(it is possible to suggest to compiler which branch will most probably be true)

```
    c = a+b;
else
    c = a-b;
```

```
        mov     eax, DWORD PTR -8[rbp]
        cmp     eax, DWORD PTR -4[rbp]
        jge     .L2
        mov     edx, DWORD PTR -8[rbp]
        mov     eax, DWORD PTR -4[rbp]
        add     eax, edx
        mov     DWORD PTR -12[rbp], eax
        jmp     .L3
.L2:
        mov     eax, DWORD PTR -8[rbp]
        sub     eax, DWORD PTR -4[rbp]
        mov     DWORD PTR -12[rbp], eax
.L3:
```

Conditional data flow

We have seen some details about the conditional transfer of the *control flow* through the simple jump mechanism.
However, that could be quite inefficient in modern CPUs (we'll se more details on that when dealing with the pipelines).

A different mechanism is to conditionally change the *data flow*, which is the second mechanism for conditional execution that we mentioned.

Conditional data flow

The conditional transfer of data flow yields a very high performance but is possible only on a small subset of cases;

basically those are when simple values are involved.

A typical example is, for instance, the absolute value of a result, or something alike where a single-valued outcome is expected.

```
if ( a < b )
  c = a+b;
else
  c = a-b;
```

Here `c` holds the result of a very simple arithmetic operation between `a` and `b`.

Conditional data flow

```
if ( a < b )
   c = a+b;
else
   c = a-b;
```

Compiled with
`gcc -O3 -march=native`

```
note:
ebx = a
eax = b
```

```
mov      edx, ebx
lea      ecx, [rbx+rax]
sub      edx, eax
cmp      eax, ebx
cmovg    edx, ecx
```

A **much** shorter and efficient code!

Conditional data flow

	eax	ebx	ecx	edx
eax = b, ebx = a	**b**	**a**	**-**	**-**
`mov edx, ebx`	**b**	**a**	**-**	**a**
`lea ecx, [rbx+rax]`	**b**	**a**	**a+b**	**a**
`sub edx, eax`	**b**	**a**	**a+b**	**a-b**
`cmp eax, ebx`	*compares a and b; sets ZF and CF (zero and carry flag)*			
`cmovg edx, ecx`	move ecx's value to edx if the condition (greater than) is satisfied			

The strategy is as follows:

(i) reg ecx contains a+b while reg edx contains a-b

(ii) the conditional move checks the result of cmp a, b (i.e. the value of a-b)

(iii) the content of edx is changed into ecx's just in case.

No jump instructions have been issued. We'll be back to this in few slides

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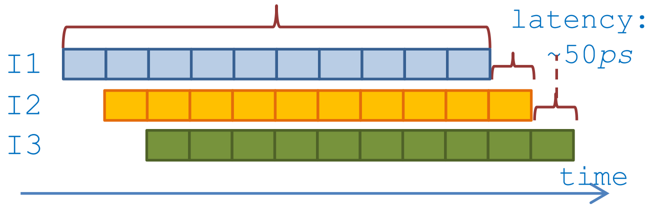
The perils of conditional branches

As we have seen in the lecture about modern architecture, **modern processors achieve great performance thanks to the *pipelines* and *out-of-order execution***, i.e. by decomposing complex instructions in simpler steps and mixing the execution of those sub-steps for different instructions (up to tens of instructions at the same time may be “on-the-fly” in modern CPUs).



We’ll see more about pipelines in forthcoming lectures

That, however, **requires the pipelines to be always full**; if not so, the toll of great penalties in terms of wasted cpu cycles is to be payed.
To achieve this goal, it is in turn mandatory for the scheduler to be able to **predict** in advance what will be the sequence of instructions to be executed.
How can that be in a world full of possibilities and branches ?

The perils of conditional branches

In order to predict what the execution flow will be, modern cpus feature a **branch predictor**, that is an internal unit of highly sophisticated logic that guesses whether a jump instruction will succeed or not.

Best branch predictors are as good as 95% of accuracy; nonetheless, the branch mis-prediction, or branch miss, determines a huge performance loss.
Typical figures for penalty are 10-30 cycles!

That is because the longer the pipeline, the further in the future you have to scrutinize the flow, the more difficult it is and the larger will be the mis-prediction penalty.

Example
Let's say we have 140 instructions in flight, and 1 every 7 is a branching instructions. What is the probability that the pipelines shall **not** *be flushed with 95% correct branch predictor? And with a 90% one?*

answer: ~36% and ~12%

The perils of conditional branches

In order to predict what the execution flow will be, modern cpus feature a **branch predictor**, that is an inter
a jump instruction will su

Best branch predictors are a
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That is because the longer t
the flow, the more difficult i

Example
Let's say we have 140 instruction
probability that the pipelines shall

That is why the 2nd strategy we have seen, the **conditional change of data flow** is preferable whenever possible and the compiler will try to use it as much as possible:

it generates no jump instructions and the execution flow is linear and perfectly predictable.

However, as we said, it applies only on a limited sub-set of case.

The perils of conditional branches

Conditional branches should be avoided as much as possible inside loops:

- moving them outside the loops and writing more specialized loops
- performing variables/quantities set-up pre-emptively outside the loops
- using pointers to functions instead of selecting functions inside the loop
- substituting conditional branches with different operations

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Clean your loops from branches

ex 1: Taking decisions before and outside the loop

```
for(i = 1; i < top; i++)
   {
     if(case1 == 0) {
       if(case2 == 0) {
          if(case3 == 0)
            result += i;
          else
            result -= i;
          }
          else {
            if(case3 == 0)
              result *= i;
            else
              result /= i;
          }
      }
```

```
else {
  if(case2 == 0) {
     if(case3 == 0)
       result += log10((double)i);
     else
       result -= log10((double)i);
     }
  else {
    if(case3 == 0)
      result *= sin((double)i);
    else
      result /= (sin((double)i) +
                 cos((double)i));
     }
  }
```

SCO/examples_on_branching/if_forest_inside_loop

Clean your loops from branches

If you do not trust your compiler to perform the *loop hoisting* for you,

- define a specialized function for each case
- **before** and **outside** the loop set a function pointer to the right function

```
void (*func)(double *, int);
<here make func pointing to the right place>

double temp   = 0;
double result = 0;
for(i = 1; i < top; i++)
   {
        func( & temp, i);
        result = temp;
    }
```

Clean your loops from branches

However:

- **Using function pointers you may incur in severe overhead due to function calls.**
  If the code snippets in different if-branches (or at least the most executed ones) are large/expensive, it might well be irrelevant (in modern CPUs).

- "Unrolling" the if-tree outside the for – then having multiple for loops may be highly unpractical if the branches are big piece of code.

There's no a Swiss-knife recipe.

```
if (case1 == 0) {
  if (case2 == 0) {
     if (case3 == 0) {
        for(i = 1; i < top; i++)
           result += i;
     else
           for(i = 1; i < top; i++)
              result -= i;
     }
```

Clean your loops from branches

In such cases it is likely much better to use the `switch` construct instead of an `if`-forest, if it is possible to translate the different tests in a test about the values of a single value:

```
switch( case )
{
  case A: …
        break;
  case B: …
        Break;

  …
  default: …
}
```

In fact, the switch construct is translated in a static table of code pointers that can be addressed directly:

```
table_of_addr[ #cases ] = { addr_A, addr_B,… , addr_N, addr_default };

if ( case > N )
   jump to addr_default;

jump to table_of_addr[ case ];
```

ex 2: code restructuring for an unpredictable datastream

Consider the following code snippet

```
// generate random numbers
for (cc = 0; cc < SIZE; cc++)
  data[cc] = rand() % TOP;

// take action depending on their value
for (ii = 0; ii < SIZE; ii++)
  {
    if (data[ii] > PIVOT)
        sum += data[ii];
  }
```

SCO/examples_on_branching/unpredictable_datastream

Revise your code

Consider the following code snippet(*)

```
// generate random numbers
for (cc = 0; cc < SIZE; cc++)
  data[cc] = rand() % TOP;

qsort(data, SIZE, sizeof(int), compare);

// take action depending on their value
for (ii = 0; ii < SIZE; ii++)
  {
    if (data[ii] > PIVOT)
       sum += data[ii];
  }
```

(*) of course, you are adding an overhead due to the sorting routine, so the total running time may be even larger. Moreover, you should have all the values available so that does not work for real-time streamings. However, the point here is to focus on how – in general – it is better to avoid conditionals inside loop, with any possible trick or change in workflow

Revise your code

You can do even better, without adding operations:

```
// generate random numbers
for (cc = 0; cc < SIZE; cc++)
  data[cc] = rand() % TOP;

// take action depending on their value
for (ii = 0; ii < SIZE; ii++)
  {
     t = (data[ii] - PIVOT -1) >> 31;
     sum += ~t & data[ii];
  }
```

Revise your code

-O0

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred
sum is 983597794767, elapsed seconds: 5.40445
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow
sum is 983597794767, elapsed seconds: 2.23186
(in total: 2.44473 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart
sum is 983597794767, elapsed seconds: 2.8878
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2%
```

-O3

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.O3
sum is 983597794767, elapsed seconds: 0.660148
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.O3
sum is 983597794767, elapsed seconds: 0.650005
(in total: 0.795181 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.O3
sum is 983597794767, elapsed seconds: 0.679286
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2%
```

Revise your code

-O3

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.O3
sum is 983597794767, elapsed seconds: 0.660148
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.O3
sum is 983597794767, elapsed seconds: 0.650005
(in total: 0.795181 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.O3
sum is 983597794767, elapsed seconds: 0.679286
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2%
```

-O3
-march=native

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.O3n
sum is 983597794767, elapsed seconds: 0.217864
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.O3n
sum is 983597794767, elapsed seconds: 0.215645
(in total: 0.355377 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.O3n
sum is 983597794767, elapsed seconds: 0.224288
```

Revise your code

What changes in the base version with –O3 ? → **conditional move**

Modern CPUs have the capability of performing *conditional move*, i.e to execute **concurrently** both branches of a conditional – **if they are “simple enough”** – and to select the right result upon the evaluation of the conditional

```
perform op1 → res in AX
perform op2 → res in BX

compare

if flag     → mov BX in AX
```

HOWEVER: loops with conditionals **are harder for vectorization !!**
(also the evaluations can be vectorized but everything may be more complicated)

Revise your code

Why the difference between **-O3** and **-O3 -march=native** ?

```
.L8:
        movdqu  xmm0, XMMWORD PTR [rax]
        movdqu  xmm6, XMMWORD PTR [rax]
        movdqa  xmm2, xmm4
        add     rax, 16
        pcmpgtd xmm0, xmm5
        pand    xmm0, xmm6
        pcmpgtd xmm2, xmm0
        movdqa  xmm3, xmm0
        punpckldq       xmm3, xmm2
        punpckhdq       xmm0, xmm2
        paddq   xmm1, xmm3
        paddq   xmm1, xmm0
        cmp     rax, rcx
        jne     .L8
```

compare 4 **integers** at a time using xmmX registers, that are common to x86_64 architectures.

bytes reshuffling to add one `int` at a time. These are SSE 128-bits instructions

increase the counter by 4 **`int`**

12 instructions to process 4 **`int`**

```
.L8:
        vmovdqu         ymm2, YMMWORD PTR [rax]
        add             rax, 32
        vpcmpgtd        ymm0, ymm2, ymm3
        vpand           ymm0, ymm0, ymm2
        vpmovsxdq       ymm2, xmm0
        vextracti128    xmm0, ymm0, 0x1
        vpaddq          ymm1, ymm2, ymm1
        vpmovsxdq       ymm0, xmm0
        vpaddq          ymm1, ymm0, ymm1
        cmp             rax, rcx
        jne             .L8
```

bytes reshuffling inside regs to add one `int` at a time
The v prefix tells you these are AVX2 256-bits instr.

compare 8 **integers** at a time using ymmX registers. This requires AVX2 that is set on by `-march=native` for this CPU

increase the counter by 8 **`int`**

9 instructions to process 8 **`int`**

Revise your code

A simpler way to transform this code

```
for (ii = 0; ii < SIZE; ii++)
  {
    if (data[ii] > PIVOT)
       sum += data[ii];
  }
```

is the following:

```
for (ii = 0; ii < SIZE; ii++)
  sum += ( data[ii]>PIVOT ) * data[ii];
```

ex 3: code restructuring for sorting two arrays

You have 2 arrays, A and B, and you want to swap their elements so that

A[i] ≥ B[i]

for all *i*.
A straightforward implementation would be:

```
for (i = 0; i < SIZE; i++)
  {
         if ( A[i] < B[i] )
            {
                  t = B[i];
                  B[i] = A[i];
                  A[i] = t; }
            }
```

SCO/examples_on_branching/sort_2_arrays

Branches | Revise your code

However, that implementation suffers exactly of the same problem we have just discussed.
An alternative way to write the same code, but in a more effective style is:

```
for (i = 0; i < SIZE; i++)
  {
     int min = A[i] > B[i] ? B[i] : A[i];
     int max = A[i] >= B[i] ? A[i] : B[i];

      A[i] = max;
      B[i] = min;
   }
```

Revise your code

```
for (uint ii = 0; ii < SIZE; ii++)
  {
    if ( B[ii] > A[ii] )
      {
        int t = A[ii];
        A[ii] = B[ii];
        B[ii] = t;
      }
```

standard

```
for (uint ii = 0; ii < SIZE; ii++)
  {
    int register t = -(A[ii]<B[ii]);
    int register x = A[ii]^B[ii];
    A[ii] = A[ii]^(x & t);
    B[ii] = B[ii]^(x & t);
```

smart2

```
for (uint ii = 0; ii < SIZE; ii++)
  {
    int max = (A[ii]>B[ii])? A[ii]:B[ii];
    int min = (A[ii]>B[ii])? B[ii]:A[ii];
    A[ii] = max;
    B[ii] = min;
```

smart

```
for (uint ii = 0; ii < SIZE; ii++)
  {
    int d = A[ii]-B[ii];
    d &= (d >> 31);
    A[ii] = A[ii] - d;
    B[ii] = B[ii] + d;
```

smart3

Standard, -O0

predictable data has a regular pattern easily spotted by the CPU's branch predictor

loop run-time

cycles per element

Instructions per element

```
1000000000 predictable numbers generation..  done

seconds            :    2.223 +- 0.004446
CPE                :         9.938 +- 0.0138
IPE                :     27.0001758 +- 3.036e-07
BRANCHES_PE        :     2.00000014 +- 6.585e-10
MISP_BRANCHES_PE   :      4.892e-07 +- 2.134e-08  ( tot:          244.6 )
```

~2.7 IPC

```
1000000000 random numbers generation..  done

seconds            :    4.501 +- 0.02864
CPE                :          27.4 +-    0.2
IPE                :     26.9996208 +- 2.98e-08
BRANCHES_PE        :     2.00000014 +- 6.585e-10
MISP_BRANCHES_PE   :    0.499933228 +- 2.215e-05  ( tot:      249966614 )
```

~1 IPC

conditional branches pert element

mis-predicted cond. branches per el.

total # of mis-predicted conditional branches

same number of IPE but almost 3 times as many CPE when data pattern is not predictable

in fact, there is 1 mis-predicted branch every 2 (arrays are 500,000,000 long)

Revise your code

smart, -O0

```
seconds           :    1.824 +- 0.05734
CPE               :          11.12 +- 0.341
IPE               :     34.0000018 +- 4.344e-08
BRANCHES_PE       :     1.00000014 +- 3.293e-10
MISP_BRANCHES_PE  :       9.94e-07 +- 3.207e-08  ( tot:           497 )
```

~3 IPC

predictable

number of IPE is larger than for standard case, but the CPE is stable !

mis-predicted branches are very few and comparable in both cases

```
seconds           :    1.857 +- 0.001762
CPE               :          11.32 +- 0.00192
IPE               :     34.0000018 +- 2.581e-08
BRANCHES_PE       :     1.00000014 +- 3.293e-10
MISP_BRANCHES_PE  :      9.512e-07 +- 4.987e-08  ( tot:         475.6 )
```

~3 IPC

random

Revise your code

smart2, -O0

predictable

```
seconds             :    1.628 +- 0.01015
CPE                 :          9.993 +- 0.0464
IPE                 :     32.0000017 +- 2.356e-08
BRANCHES_PE         :     1.00000014 +- 3.293e-10
MISP_BRANCHES_PE    :      3.728e-07 +- 8.898e-08  ( tot:        186.4 )
```

~3 IPC

number of IPE is larger than for standard case, but the CPE is stable !

mis-predicted branches are very few and comparable in both cases

random

```
seconds             :    1.688 +- 0.03554
CPE                 :          10.36 +- 0.211
IPE                 :     32.0000017 +- 2.98e-08
BRANCHES_PE         :     1.00000014 +- 3.293e-10
MISP_BRANCHES_PE    :        3.1e-07 +- 5.183e-08  ( tot:          155 )
```

~3 IPC

Comments on the previous slides

The standard implementation relies on the ability of your CPU's branch predictor to guess the correct data pattern.
When it is successful, it is **really** so (it exhibits the lowest CPE and IPE).

However, whenever the data pattern is not guessable by the branch predictor things quickly become really weird.

Writing the code differently may make you loosing something in terms of CPE/IPE (with respect to the best possible standard case) but not really in terms of time-to-solution.
And, above all, the code behaviour is **stable** with both predictable and unpredictable patterns.

std implementation, -O0

```
.L20:
        mov     eax, DWORD PTR -88[rbp] #  ii
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -56[rbp] #  B
        add     rax, rdx
        mov     edx, DWORD PTR [rax]
        mov     eax, DWORD PTR -88[rbp] #  ii
        lea     rcx, 0[0+rax*4]
        mov     rax, QWORD PTR -64[rbp] #  A
        add     rax, rcx
        mov     eax, DWORD PTR [rax]
# branchpred2.c:116:                 if ( B[ii] > A[ii] )
        cmp     edx, eax
        jle     .L19
# branchpred2.c:118:                int t = A[ii];
        mov     eax, DWORD PTR -88[rbp] #  ii
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -64[rbp] #  A
        add     rax, rdx
# branchpred2.c:118:                int t = A[ii];
        mov     eax, DWORD PTR [rax]
        mov     DWORD PTR -84[rbp], eax # t
# branchpred2.c:119:                A[ii] = B[ii];
        mov     eax, DWORD PTR -88[rbp] # ii
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -56[rbp] #  B
        add     rax, rdx         #
# branchpred2.c:119:                A[ii] = B[ii];
        mov     edx, DWORD PTR -88[rbp] # ii
        lea     rcx, 0[0+rdx*4]
        mov     rdx, QWORD PTR -64[rbp] # A
        add     rdx, rcx
# branchpred2.c:119:                A[ii] = B[ii];
        mov     eax, DWORD PTR [rax]
# branchpred2.c:119:                A[ii] = B[ii];
        mov     DWORD PTR [rdx], eax
# branchpred2.c:120:                B[ii] = t;
        mov     eax, DWORD PTR -88[rbp] # ii
        lea     rdx, 0[0+rax*4] ,
        mov     rax, QWORD PTR -56[rbp] # B
        add     rdx, rax         #
# branchpred2.c:120:                B[ii] = t;
        mov     eax, DWORD PTR -84[rbp] # t
        mov     DWORD PTR [rdx], eax
.L19:
# branchpred2.c:112:           for (uint ii = 0; ii < SIZE; ii++)
        add     DWORD PTR -88[rbp], 1   # ii,
.L18:
# branchpred2.c:112:           for (uint ii = 0; ii < SIZE; ii++)
        mov     eax, DWORD PTR -88[rbp] # ii
        cmp     eax, DWORD PTR -120[rbp]        # SIZE
        jb      .L20
```

1 cmp instr. with a following jump

2 cmov instr. can use 2 pipelines

smart implementation, -O0

```
.L19:
# branchpred2.c:122:         max = A[ii] > B[ii] ? A[ii] : B[ii];
        mov     eax, DWORD PTR -92[rbp] # tmp229, ii
        cdqe
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -56[rbp] #  B
        add     rax, rdx
        mov     edx, DWORD PTR [rax]
        mov     eax, DWORD PTR -92[rbp] #  ii
        cdqe
        lea     rcx, 0[0+rax*4] # _51,
        mov     rax, QWORD PTR -64[rbp] #  A
        add     rax, rcx
        mov     eax, DWORD PTR [rax]
# branchpred2.c:122:         max = A[ii] > B[ii] ? A[ii] : B[ii];
        cmp     edx, eax
        cmovge  eax, edx
        mov     DWORD PTR -88[rbp], eax # max
# branchpred2.c:123:         min = A[ii] < B[ii] ? A[ii] : B[ii];
        mov     eax, DWORD PTR -92[rbp] # ii
        cdqe
        lea     rdx, 0[0+rax*4] # _55,
        mov     rax, QWORD PTR -56[rbp] #  B
        add     rax, rdx        # _56, _55
        mov     edx, DWORD PTR [rax]
# branchpred2.c:123:         min = A[ii] < B[ii] ? A[ii] : B[ii];
        mov     eax, DWORD PTR -92[rbp] #  ii
        cdqe
        lea     rcx, 0[0+rax*4] # _59,
        mov     rax, QWORD PTR -64[rbp] #  A
        add     rax, rcx
        mov     eax, DWORD PTR [rax]
# branchpred2.c:123:         min = A[ii] < B[ii] ? A[ii] : B[ii];
        cmp     edx, eax
        cmovle  eax, edx
        mov     DWORD PTR -84[rbp], eax # min
# branchpred2.c:131:         A[ii] = max;
        mov     eax, DWORD PTR -92[rbp] #  ii
        cdqe
        lea     rdx, 0[0+rax*4]
        mov     rax, QWORD PTR -64[rbp] #  A
        add     rdx, rax
# branchpred2.c:131:         A[ii] = max;
        mov     eax, DWORD PTR -88[rbp] #  max
        mov     DWORD PTR [rdx], eax
# branchpred2.c:132:         B[ii] = min;
        mov     eax, DWORD PTR -92[rbp] #  ii
        cdqe
        lea     rdx, 0[0+rax*4] # _66,
        mov     rax, QWORD PTR -56[rbp] #  B
        add     rdx, rax
# branchpred2.c:132:         B[ii] = min;
        mov     eax, DWORD PTR -84[rbp] #  min
        mov     DWORD PTR [rdx], eax
# branchpred2.c:107:          for (ii = 0; ii < SIZE; ii++)
        add     DWORD PTR -92[rbp], 1   # ii,
.L18:
# branchpred2.c:107:          for (ii = 0; ii < SIZE; ii++)
        mov     eax, DWORD PTR -92[rbp] #  ii
        cmp     eax, DWORD PTR -104[rbp] #  SIZE
        jl      .L19
```

Performance of different versions with predictable data (gcc)

opt	smart	data	time +-	err	CPE +-	err	INS +-	err	BRE
O0	N	P	1.697e+00	+- 2.876e-03	1.041e+01	+- 6.740e-04	2.700e+01	+- 3.650e-08	2.000e+00
O0	smart	P	1.859e+00	+- 5.434e-02	1.118e+01	+- 3.320e-01	3.400e+01	+- 3.406e-07	1.000e+00
O0	smart2	P	1.815e+00	+- 2.680e-03	1.114e+01	+- 9.030e-03	3.700e+01	+- 3.942e-08	1.000e+00
O0	smart3	P	1.628e+00	+- 1.015e-02	9.993e+00	+- 4.640e-02	3.200e+01	+- 2.356e-08	1.000e+00
O3	N	P	6.448e-01	+- 3.248e-03	3.578e+00	+- 2.550e-03	8.000e+00	+- 2.849e-08	2.000e+00
O3	smart	P	4.548e-01	+- 7.833e-03	2.064e+00	+- 2.040e-02	4.250e+00	+- 3.953e-08	2.500e-01
O3	smart2	P	4.506e-01	+- 1.419e-03	2.109e+00	+- 1.650e-02	4.500e+00	+- 3.723e-08	2.500e-01
O3	smart3	P	4.332e-01	+- 2.937e-03	1.905e+00	+- 6.180e-03	3.500e+00	+- 2.542e-08	2.500e-01
O3n	N	P	3.518e-01	+- 1.096e-02	1.357e+00	+- 1.410e-02	1.125e+00	+- 4.850e-09	2.500e-01
O3n	smart	P	3.905e-01	+- 2.258e-03	1.367e+00	+- 1.030e-02	1.125e+00	+- 2.643e-08	1.250e-01
O3n	smart2	P	4.114e-01	+- 1.941e-02	1.671e+00	+- 5.650e-02	1.750e+00	+- 3.118e-08	1.250e-01
O3n	smart3	P	4.119e-01	+- 3.449e-03	1.523e+00	+- 1.500e-02	1.500e+00	+- 1.613e-09	1.250e-01

The standard implementation (label "N" in the table) exhibits a better behaviour at –O0 considering CPE and above all IPE (label "INS" in the table), whereas run times are comparable among different variants (std, smart, smart2 and smart3).

However, at –O3 its behaviour is the worst one, with CPE larger by ~75% and IPE larger by a factor of ~2. Only with very aggressive optimization the compiler can generate a code comparable with the smartX ones

Performance of different versions with non-predictable data (gcc)

opt	smart	data	time +-	err	CPE +-	err	INS +-	err	BRE
O0	N	R	4.426e+00 +-	2.966e-02	2.725e+01 +-	1.830e-01	2.700e+01 +-	2.788e-08	2.000e+00
O0	smart	R	1.855e+00 +-	1.822e-03	1.139e+01 +-	1.860e-03	3.400e+01 +-	3.161e-08	1.000e+00
O0	smart2	R	1.718e+00 +-	5.001e-02	1.055e+01 +-	2.940e-01	3.700e+01 +-	3.942e-08	1.000e+00
O0	smart3	R	1.688e+00 +-	3.554e-02	1.036e+01 +-	2.110e-01	3.200e+01 +-	2.980e-08	1.000e+00
O3	N	R	2.306e+00 +-	1.549e-02	1.418e+01 +-	8.650e-02	8.000e+00 +-	4.292e-08	2.000e+00
O3	smart	R	4.178e-01 +-	3.808e-02	2.138e+00 +-	7.510e-02	4.250e+00 +-	3.838e-08	2.500e-01
O3	smart2	R	4.517e-01 +-	1.640e-03	2.098e+00 +-	1.450e-02	4.500e+00 +-	2.644e-08	2.500e-01
O3	smart3	R	4.321e-01 +-	2.602e-03	1.910e+00 +-	1.260e-02	3.500e+00 +-	2.710e-08	2.500e-01
O3n	N	R	4.178e-01 +-	3.130e-03	1.600e+00 +-	6.140e-03	1.249e+00 +-	2.661e-08	2.500e-01
O3n	smart	R	3.918e-01 +-	1.255e-03	1.363e+00 +-	1.260e-02	1.125e+00 +-	2.602e-08	1.250e-01
O3n	smart2	R	4.107e-01 +-	1.860e-02	1.653e+00 +-	3.830e-02	1.750e+00 +-	9.429e-09	1.250e-01
O3n	smart3	R	4.131e-01 +-	1.929e-03	1.516e+00 +-	9.290e-03	1.500e+00 +-	1.397e-09	1.250e-01

When dealing with random data, the difference between std implementation and the other ones is even more obvious up to –O3, with the CPE being larger by a factor of ~3 and ~4 than in predictable data case at –O0 and –O3 respectively.

With very aggressive optimization the compiler can generate a code comparable with the smartX ones (for this very simple code snippet).

Let’s now try with a different compiler…

Conditional branches with pgi compiler (v 18.10-0)

opt	smart	data	time +-	err	CPE +-	err	INS +-	err	BRE
O0	N	P	9.380e-01 +-	5.053e-03	5.443e+00 +-	4.480e-03	1.700e+01 +-	3.373e-08	2.000e+00
O0	N	R	3.263e+00 +-	1.724e-02	1.982e+01 +-	2.920e-02	1.700e+01 +-	7.580e-08	2.000e+00
O0	smart	P	1.671e+00 +-	5.070e-02	1.016e+01 +-	3.010e-01	3.300e+01 +-	2.788e-08	3.000e+00
O0	smart	R	4.132e+00 +-	4.019e-02	2.525e+01 +-	2.350e-01	3.300e+01 +-	4.344e-08	3.000e+00
O0	smart2	P	1.848e+00 +-	3.021e-03	1.126e+01 +-	1.530e-02	3.000e+01 +-	2.471e-08	1.000e+00
O0	smart2	R	1.775e+00 +-	6.319e-02	1.082e+01 +-	3.790e-01	3.000e+01 +-	6.909e-08	1.000e+00
O0	smart3	P	1.362e+00 +-	6.870e-02	8.283e+00 +-	4.140e-01	2.300e+01 +-	3.573e-08	1.000e+00
O0	smart3	R	1.462e+00 +-	2.043e-03	8.873e+00 +-	8.040e-03	2.300e+01 +-	4.012e-08	1.000e+00
O3	N	P	5.530e-01 +-	1.608e-03	3.010e+00 +-	6.270e-03	7.500e+00 +-	5.952e-08	2.000e+00
O3	N	R	2.343e+00 +-	1.076e-02	1.428e+01 +-	6.810e-02	7.500e+00 +-	2.998e-08	2.000e+00
O3	smart	P	3.788e-01 +-	2.156e-03	1.772e+00 +-	4.020e-02	1.875e+00 +-	1.867e-08	2.500e-01
O3	smart	R	3.780e-01 +-	1.939e-03	1.769e+00 +-	2.440e-02	1.875e+00 +-	1.073e-08	2.500e-01
O3	smart2	P	4.013e-01 +-	1.917e-03	2.210e+00 +-	4.540e-03	3.125e+00 +-	4.165e-09	2.500e-01
O3	smart2	R	4.011e-01 +-	1.736e-03	2.212e+00 +-	6.520e-03	3.125e+00 +-	1.863e-09	2.500e-01
O3	smart3	P	3.862e-01 +-	4.548e-03	2.080e+00 +-	2.630e-02	2.375e+00 +-	9.701e-09	2.500e-01
O3	smart3	R	3.873e-01 +-	2.408e-03	2.067e+00 +-	9.120e-03	2.375e+00 +-	2.734e-08	2.500e-01
O3n	N	P	5.538e-01 +-	2.179e-03	3.012e+00 +-	5.910e-03	7.500e+00 +-	1.070e-08	2.000e+00
O3n	N	R	2.403e+00 +-	1.996e-02	1.464e+01 +-	1.010e-01	7.500e+00 +-	3.822e-08	2.000e+00
O3n	smart	P	3.759e-01 +-	2.942e-03	1.776e+00 +-	2.770e-02	1.875e+00 +-	3.132e-08	2.500e-01
O3n	smart	R	3.831e-01 +-	2.355e-03	1.746e+00 +-	1.320e-02	1.875e+00 +-	7.552e-09	2.500e-01
O3n	smart2	P	4.047e-01 +-	4.673e-03	2.225e+00 +-	9.760e-03	3.125e+00 +-	1.050e-08	2.500e-01
O3n	smart2	R	4.019e-01 +-	1.069e-03	2.214e+00 +-	7.920e-03	3.125e+00 +-	2.281e-09	2.500e-01
O3n	smart3	P	3.848e-01 +-	3.987e-03	2.054e+00 +-	1.290e-02	2.375e+00 +-	3.029e-08	2.500e-01
O3n	smart3	R	3.836e-01 +-	1.914e-03	2.048e+00 +-	3.770e-03	2.375e+00 +-	2.684e-08	2.500e-01

Comments on the previous slides

As we have seen, the `gcc` compiler can generate a code comparable to what it does with `smartX` variants only with very aggressive optimization and using AVX 256-bits instructions.

When random data are used, the standard implementation exhibits a behaviour that is much worse than with data with a predictable pattern, whereas trying not to use conditional branches generates a more stable code.

In this case, `pgi` compiler proves to be less able than `gcc` to generate optimal code, with `-O3n` level (*) still having a pronounced spike in CPE for random data.

Bottom-line is: **do not take it for granted that you lit up the compiler's optimization and everything will go seamlessly towards a triumph**.

(*) actually it is `-O4 -fast -tp haswell -Mvect=simd:256`

Change the point of view

ex. 4: about the fact that design and simplicity are the best move

Just changing point of view sometimes may help:

This code initializes a `NxM` matrix so that the eelements int top-right triangle are set to `1.0`, the entries in the diagonal i=j are set to `0.0` and the bottom-left part is set to `-1.0`

```
for ( j = 0; j < N; j++ )
    for ( i = 0; i < M; i++ )
        {
            if ( i > j )
               matrix[j][i] = 1.0;
            else if ( i < j )
               matrix[j][i] = -1.0;
            else
               matrix[j][i] = 0.0;
         }
```

Change the point of view

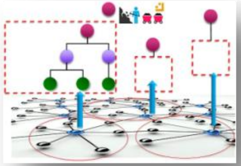
Can easily be re-written with no conditional evaluations at all:

```
for ( int j = 0; j < N; j++ )
   {
       int i;
       for ( i = 0; i < j; i++ )
           matrix[j][i] = -1.0;

       matrix[j][i] = 0.0;

       for ( i = j+1; i < M; i++ )
            matrix[j][i] = 1.0;
   }
```

A word of caution

It may be really easy to get lost in "optimization", in hunting every single line wondering why some incredible trick that – you're convinced – should work, actually does not.

"Optimization" includes also optimizing your effort and your time, so always **remember that the most important ingredients** are **by far**:



The algorithms that you choose

The data model you design

The overall quality, cleanness and robustness of your code

that’s all, have fun