

# Modern Architectures & Optimization

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**“Foundation of HPC” course**

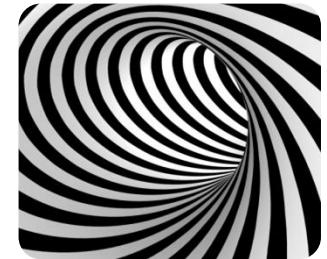


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Optimization



# Outline



Branches

Pipelines

Loops



Branches

# | 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



Branches

# Low-level control

Let's see the conditional execution flow as first.

At machine level, the way to alter the execution flow is through **jump instructions**, 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.



**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 the characteristics 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.

|            |                           |                              |
|------------|---------------------------|------------------------------|
| <b>jmp</b> | <i>Label<br/>*Operand</i> | direct jump<br>indirect jump |
| <b>je</b>  | <i>Label</i>              | jump if equal / zero         |
| <b>jne</b> | <i>Label</i>              | jump if not equal / zero     |
| <b>js</b>  | <i>Label</i>              | jump if negative             |
| <b>jns</b> | <i>Label</i>              | jump if not negative         |
| <b>jg</b>  | <i>Label</i>              | jump if greater              |
| <b>jge</b> | <i>Label</i>              | jump if greater or equal     |
| <b>jl</b>  | <i>Label</i>              | jump if less                 |
| ...        | ...                       | ...                          |



Branches

# Low-level example: for loop

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

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

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

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

.L2:

mov  
add  
cmp  
jne

DWORD PTR [rax], 0  
rax, 4  
rax, rbp  
.L2

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

ax contains the address of array

jump if not equal, i.e. jumps to .L2 if the *zf* flag is not set



Branches

# Low-level example: for loop

This is the linear flow of execution in the cycle body



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

```
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
```

.L2:

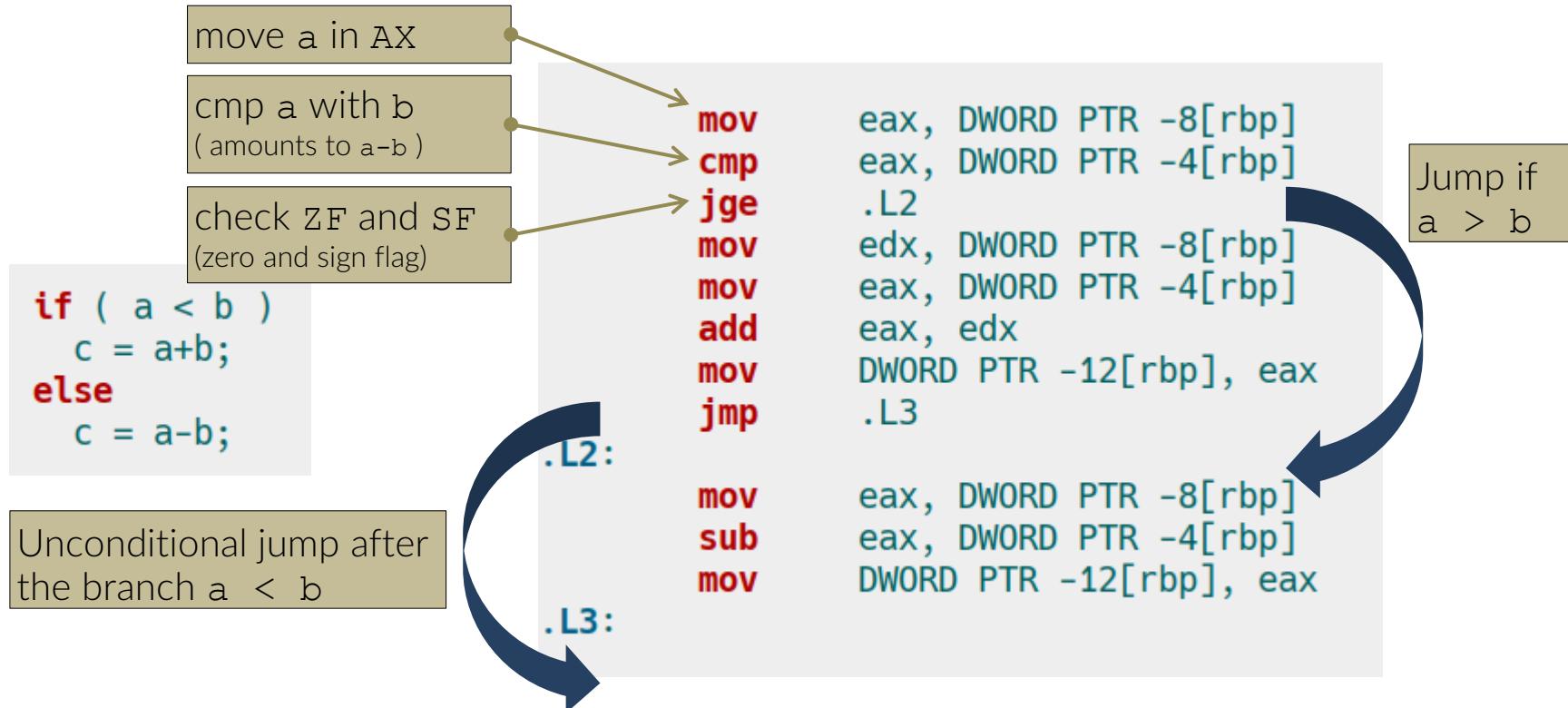
.L3:

Note: compiled without optimization, though



Branches

# Low-level example: if statement





Branches

# 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, pay attention to what is most likely to be true if possible, to preserve the code locality

```
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:
```



# 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 see more details on that when dealing with the pipelines).

A different mechanism is to **conditionally change the data flow**, which is the second one that we mentioned [before](#).



Branches

# 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  $b$ .



Branches

# Conditional data flow

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

Compiled with  
gcc -O3 -march=native

ebx = a  
eax = b

|              |                |
|--------------|----------------|
| <b>mov</b>   | edx, ebx       |
| <b>lea</b>   | ecx, [rbx+rax] |
| <b>sub</b>   | edx, eax       |
| <b>cmp</b>   | eax, ebx       |
| <b>cmove</b> | edx, ecx       |

A much shorter and efficient code!



Branches

# Conditional data flow

|                               | <b>eax</b>                                                           | <b>ebx</b> | <b>ecx</b> | <b>edx</b> |
|-------------------------------|----------------------------------------------------------------------|------------|------------|------------|
| <code>eax = b, ebx = a</code> | <b>b</b>                                                             | <b>a</b>   | -          | -          |
| <b>mov edx, ebx</b>           | <b>b</b>                                                             | <b>a</b>   | -          | <b>a</b>   |
| <b>lea ecx, [rbx+rax]</b>     | <b>b</b>                                                             | <b>a</b>   | <b>a+b</b> | <b>a</b>   |
| <b>sub edx, eax</b>           | <b>b</b>                                                             | <b>a</b>   | <b>a+b</b> | <b>a-b</b> |
| <b>cmp eax, ebx</b>           | <i>compares a and b; sets ZF and CF (zero and carry flag)</i>        |            |            |            |
| <b>cmove edx, ecx</b>         | 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.

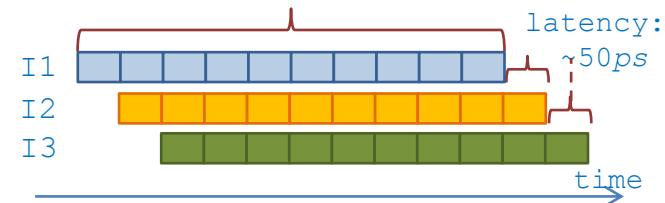


Branches

# 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).

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 ?**



We'll see more about pipelines in forthcoming lectures



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 values 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 on the 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 internal mechanism that tries to guess the outcome of a branch instruction. That is why the 2<sup>nd</sup> 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:

Best branch predictors are able to correctly predict the outcome of a branch instruction in 95% of the cases. In case of prediction miss, or branch misprediction, the CPU needs to take a recovery path. The penalties for a misprediction are 10-30 cycles!

That is because the longer the execution flow is, the more difficult it is to predict the flow, the more difficult it is to predict the flow.

## Example

Let's say we have 140 instructions. What is the probability that the pipelines shall be empty at the end of the execution?

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 cases.



Branches

# 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



Branches

# 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));
        }
    }
}
```



# 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 pointless (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;  
    } } }
```



Branches

# Clean your loops from branches

In such cases it is likely much better to use the `switch` construct instead of an `if-forest`, 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 ];
```



# Restruct your code

## ex 2: code restructuring

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];
}
```



# Restruct your code

Consider the following code snippet<sup>(\*)</sup>

```
// 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];
}
```

<sup>(\*)</sup>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



# Restruct 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];
}
```



# Restruct your code

-00

```
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% █
```

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.03
sum is 983597794767, elapsed seconds 0.660148
```

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.03
sum is 983597794767, elapsed seconds: 0.650005
(in total: 0.795181 seconds)
```

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.03
sum is 983597794767, elapsed seconds: 0.679286
```

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% █
```



Branches

# Restruct your code

-03

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.03
sum is 983597794767, elapsed seconds: 0.660148
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.03
sum is 983597794767, elapsed seconds: 0.650005
(in total: 0.795181 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.03
sum is 983597794767, elapsed seconds: 0.679286
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% █
```

-03

**-march=native**

```
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.03n
sum is 983597794767, elapsed seconds: 0.217864
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.wow.03n
sum is 983597794767, elapsed seconds: 0.215645
(in total: 0.355377 seconds)
luca@GGG:~/code/HPC_LECTURES/branch_prediction/branch_prediction_2% ./branchpred.smart.03n
sum is 983597794767, elapsed seconds: 0.224288
```



Branches

# Restruct 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 can not be fully vectorized !!



# Restruct your code

Why the difference in the base v. between **-O3** and **-O3 -march=native** ?

.L8:

```
movdqu xmm0, XMMWORD PTR [rax]
movdqu xmm6, XMMWORD PTR [rax]
movdqa xmm2, xmm4
add rax, 16
pcmpgt�d xmm0, xmm5
pand xmm0, xmm6
pcmpgt�d 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.

increase the counter by **4 int**

12 instructions to process **4 int**

.L8:

```
vmovdqu
add
vpcmpgt�d
vpand
vpmovsxdq
vextracti128
vpaddq
vpmovsxdq
vpaddq
cmp
jne
```

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

9 instructions to process **8 int**

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**



Branches

# Restruct your code

We can do slightly better:

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

can be changed to

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



# Restruct your code

Let's look to another practical example

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

$$A[i] \geq B[i]$$

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; }
}
```



# Restruct 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;
}
```



Branches

# Restruct 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

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

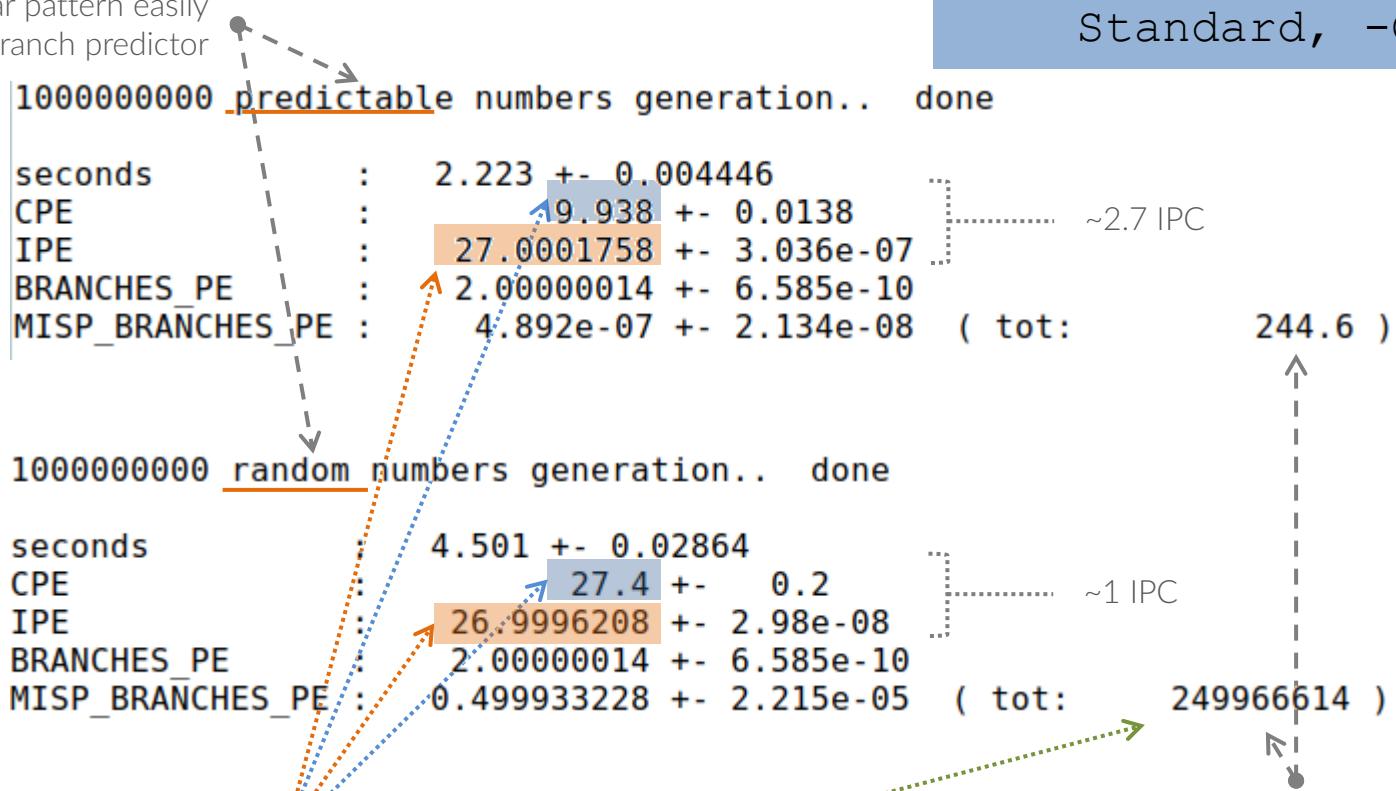
Standard, -00

loop run-time  
cycles per element  
Instructions per element

conditional branches  
pert element  
mis-predicted cond.  
branches per el.

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 )



total # of mis-predicted  
conditional branches



Branches

# Restruct your code

seconds

CPE

IPE

BRANCHES\_PE

MISP\_BRANCHES\_PE

1.824 +- 0.05734

11.12 +- 0.341

34.0000018 +- 4.344e-08

1.00000014 +- 3.293e-10

9.94e-07 +- 3.207e-08 ( tot:

~3 IPC

smart, -00

**predictable**

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

497 )

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

seconds

CPE

IPE

BRANCHES\_PE

MISP\_BRANCHES\_PE

1.857 +- 0.001762

11.32 +- 0.00192

34.0000018 +- 2.581e-08

1.00000014 +- 3.293e-10

9.512e-07 +- 4.987e-08 ( tot:

~3 IPC

**random**

475.6 )



Branches

# Restruct your code

```
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:
```

~3 IPC

smart2, -00

**predictable**

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

186.4 )

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

```
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:
```

~3 IPC

**random**

155 )



Branches

# Restruct your code

```
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:
```

~3 IPC

smart3, -00

**predictable**

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

186.4 )

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

```
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:
```

~3 IPC

**random**

155 )



# *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.

.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
```

## std implementation, -O0

1 cmp instr. with  
a following jump

2 cmov instr.  
can use 2  
pipelines

.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
```

## smart implementation, -O0



# Comparison with predictable data

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



# Comparison with non-predictable data

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



Branches

## Conditional branches with pgi compiler (v 18.10-0)

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



Branches

# *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`



Branches

# | Change the point of view

A last example.. about the fact that design and simplicity are the best move

Just changing point of view sometimes may help:

```
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;
    }
```



Branches

# | Change the point of view

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

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

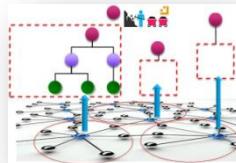
    matrix[j][i] = 0.0;

    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, cleanliness and robustness of your code

that's all, have fun

"So long  
and thanks  
for all the fish"