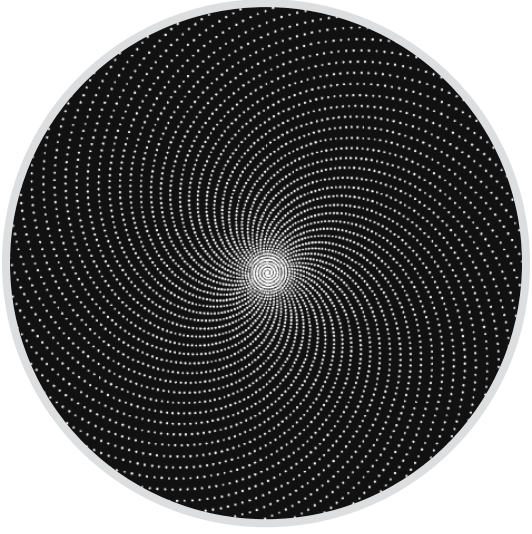
Branchless Programming

"How to make your code faster and less readable."

```
public static T CountBitsSetTo1<T>(T v)
{
    v = v - ((v >> 1) & (T)~(T)0/3);                           // temp
    v = (v & (T)~(T)0/15*3) + ((v >> 2) & (T)~(T)0/15*3);      // temp
    v = (v + (v >> 4)) & (T)~(T)0/255*15;                      // temp
    return (T)(v * ((T)~(T)0/255)) >> (sizeof(T) - 1) * CHAR_BIT; // count
}
```

example taken from "Bit Twiddling Hacks" by Sean Eron Anderson

Sooo... who is this guy?



`frederik-hoeft`

.NET guy studying computer science.
Interested in low level stuff, cryptography and cyber security.

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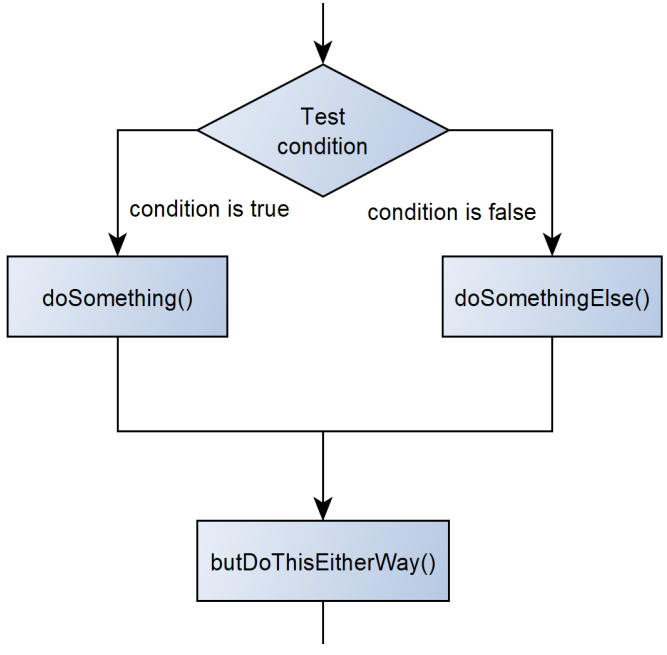
- 😐 thinks he's funny...
- 👨‍🎓 5th semester CS student @FHDW Hannover
- 💼 full-stack mobile / web dev @WKG Software GmbH
- 💼 freelancing since 2020
- 👨‍💻 since 2018

Structure

- What are branches and why should I care?
  - An "everyday" example
- Branchless programming
  - The CPU, x86 assembly and pipelining
  - Bits, bytes and binary arithmetic
- Going branchless
- Some benchmarks
- Branchless is just the beginning
- Pitfalls, Do's and Dont's
- Questions

What are branches?

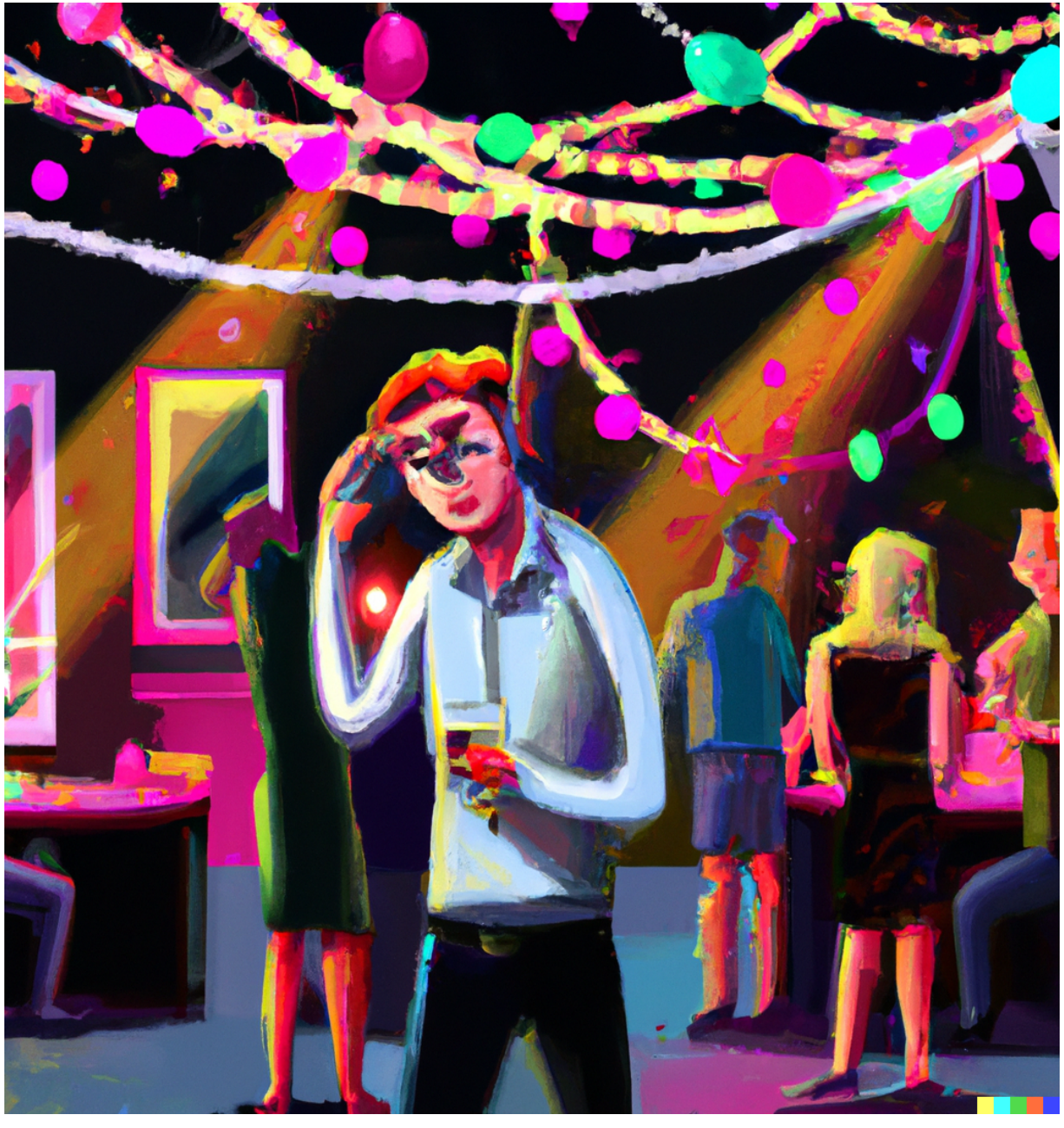
```
if (condition)
{
    doSomething();
}
else
{
    doSomethingElse();
}
butDoThisEitherWay();
```



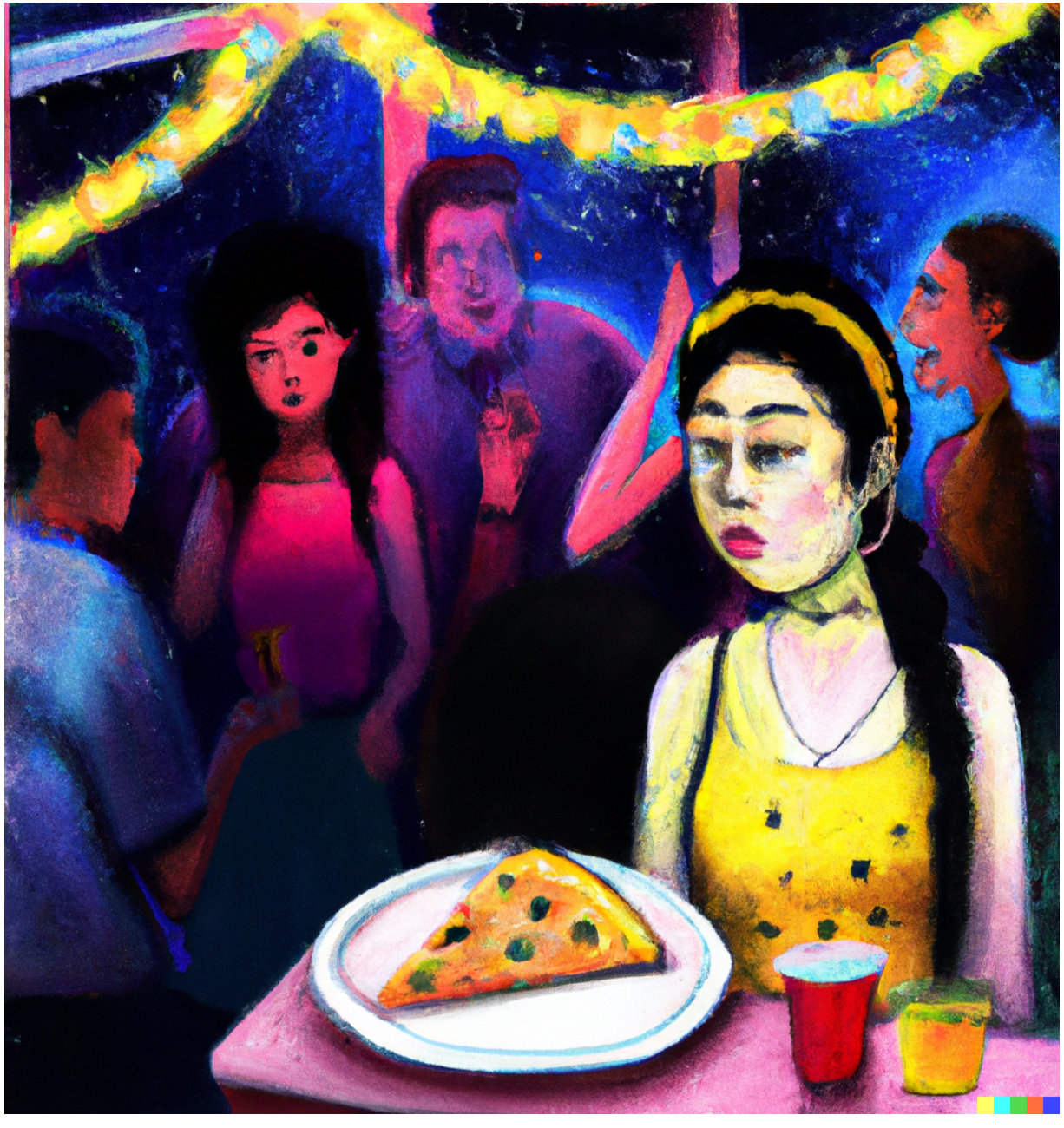
Cool... So what's wrong with it?

An introductory example

"It's Friday. This is what you could be doing right now." by DALL·E (OpenAI)

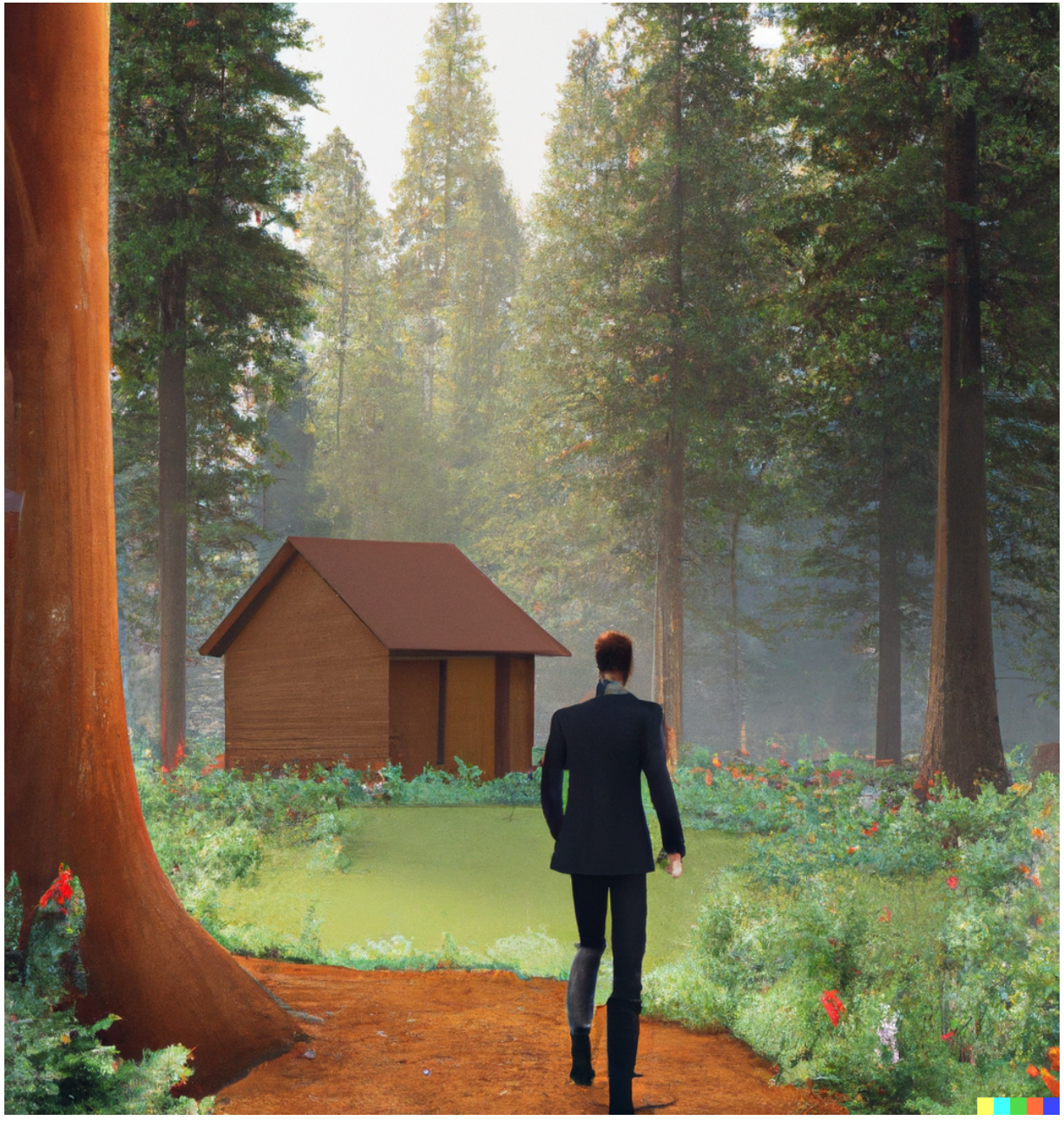


"Waiting for branch evaluation." by DALL·E (OpenAI)



"Branch evaluated: friendship assertion failed. Reason: 'pineapple pizza'." by DALL·E (OpenAI)

"Eliminate branches: just order everything. Also: wth is happening?" by DALL·E (OpenAI)



"Consequences of (over-) using branchless programming." by DALL·E (OpenAI)

For real:
what *is* ”branchless programming”?

- advanced optimization technique for low-level code
  - *"making things faster"*
- Eliminate branches in `if`, `switch` statements.
  - *not* loops (`while`, `for`, ...) $\implies$ "loop unrolling"

Let's see why branches can be slow...

How does it work?

Our code:

```
int AbsoluteOf(int number)
{
    if (number >= 0) // condition
    {
        return number; // option 1
    }
    else
    {
        return number * (-1); // option 2
    }
}
```

What the CPU sees:

```
int AbsoluteOf(int number)
{
    if (number >= 0) // condition
    {
        return number; // option 1
    }
    else
    {
        return number * (-1); // option 2
    }
}
```

```
// result is eax
// number is edx
AbsoluteOf(Int32)
    L0000: test edx, edx // condition
    L0002: jl short L0007
    L0004: mov eax, edx // option 1
    L0006: ret
    L0007: mov eax, edx // option 2
    L0009: neg eax
    L000b: ret
```

$\Longrightarrow$ instructions: `test, jl, mov, ret, mov, neg, ret`

What the CPU does

You won't believe these 4 simple steps to execute an instruction:

1. Instruction Fetch (IF) *"Give me an instruction"*
2. Instruction Decode (ID) *"K thx. So what do I need to do?"*
3. Execute (EX) *"Ah okay. I'm doing it."*
4. Write back (WB) *"Yay I did it. Here's the result."* 😃

- Repeat...

time	**IF**	→	**ID**	→	**EX**	→	**WB**
1t	`mov`						
2t			`mov`				
3t					`mov`		
4t							`mov`

Pipelining

Just process multiple instructions at once:

instructions: `mov, add, mov, sub, ...`

time	**IF**	$\rightarrow$	**ID**	$\rightarrow$	**EX**	$\rightarrow$	**WB**
1t	`mov`						
2t	`add`		`mov`				
3t	`mov`		`add`		`mov`		
4t	`sub`		`mov`		`add`		`mov`

Back to our example

```
AbsoluteOf(Int32)
    L0000: test edx, edx // condition
    L0002: jl short L0007
    L0004: mov eax, edx // option 1
    L0006: ret
    L0007: mov eax, edx // option 2
    L0009: neg eax
    L000b: ret
```

$\Longrightarrow$

time	IF	→	ID	→	EX	→	WB
1t	test						
2t	jl		test				
3t	😴		jl		test		
4t	😴		😴		jl		test

$\Longrightarrow$ Pipeline stall: wait for branch evaluation!

Branch elimination

Branching

```
int AbsoluteOf(int number)
{
    if (number >= 0) // condition
    {
        return number; // option 1
    }
    else
    {
        return number * (-1); // option 2
    }
}
```

Branchless

```
Int32 AbsoluteOf(Int32 number)
{
    Int32 mask = (number >> 31);
    return number * (mask | 1);
}
```

```
Int32 AbsoluteOf(Int32 number)
{
    Int32 mask = (number >> 31);

    return (number + mask) ^ mask;
}
```

"Yeah, cool... But what is happening here?"

Two's complement

How are negative numbers stored?

positive decimal	positive binary	negative binary	negative decimal
10^0	$2^3 2^2\ 2^1 2^0$	$-2^3 2^2\ 2^1 2^0$	-10^0
0	$0\ 0\ 0\ 0$	$0\ 0\ 0\ 0$	$-\ 0$
1	$0\ 0\ 0\ 1$	$1\ 1\ 1\ 1$	$-\ 1$
2	$0\ 0\ 1\ 0$	$1\ 1\ 1\ 0$	$-\ 2$
3	$0\ 0\ 1\ 1$	$1\ 1\ 0\ 1$	$-\ 3$
4	$0\ 1\ 0\ 0$	$1\ 1\ 0\ 0$	$-\ 4$
5	$0\ 1\ 0\ 1$	$1\ 0\ 1\ 1$	$-\ 5$
6	$0\ 1\ 1\ 0$	$1\ 0\ 1\ 0$	$-\ 6$
7	$0\ 1\ 1\ 1$	$1\ 0\ 0\ 1$	$-\ 7$
8	$-\ -\ -\ -$	$1\ 0\ 0\ 0$	$-\ 8$

$\Longrightarrow\ x \cdot (-1) = x - 1$, then invert bits.

Binary arithmetic

or: |		**and: &**		**xor: ^**
1001		1001		1001
| 0011	&	0011	^	0011
= 1011	=	0001	=	1010

flip bits: ~		**signed shift right by x: >>x**
~ 1001		1001 >>2
= 0110	=	1110

Back to our example

```
Int32 AbsoluteOf(Int32 number)
{
    Int32 mask = (number >> 31);
    return number * (mask | 1);
}
```

- `Int32` $\Longrightarrow$ 32 bit signed integer
- `>> 31` $\Longrightarrow$ signed bit-shift right by 31 bits.
- `| 1` $\Longrightarrow$ "or 1"

Let's test this.

What if number = 5?

- number = 5 = 0 . . . 0101b
- mask = 0 . . . 0b = 0
- (mask | 1) = 0 . . . 0b | 0 . . . 1b = 1
- number * (mask | 1) = 5 * 1 = 5

What if number = -3?

- number = -3 $\Longrightarrow$ 1 . . . 1101b
- mask = 1 . . . 1b = -1
- (mask | 1) = 1 . . . 1b | 0 . . . 1b = 1 . . . 1b = -1
- number * (mask | 1) = -3 * (-1) = 3

Aha, so it is calculating

- number * (0 | 1) = number * 1, if number is positive
- number * (-1 | 1) = number * -1, if number is negative

What about the other version?

```
Int32 AbsoluteOf(Int32 number)
{
    Int32 mask = (number >> 31);
    return (number + mask) ^ mask;
}
```

- `Int32` $\Longrightarrow$ 32 bit signed integer
- `>> 31` $\Longrightarrow$ copy sign bit 31 times.
- `^` $\Longrightarrow$ "xor"
- `mask` will be 0 (all 0) or -1 (all 1).

Let's test this.

What if number = 5?

- 5 is positive, so mask will be 0.
- number + mask = 5 + 0 = 5
- 5 ^ mask = 5 ^ 0
- xor all 0s does nothing
- $\Longrightarrow$ 5 ^ 0 = 5

What if number = -3?

- -3 is negative, so mask will be -1 (all bits set to 1).
- number + mask = -3 + (-1) = -4
- -4 ^ mask = -4 ^ (-1)
- xor all 1s inverts all bits
- $\Longrightarrow$ -4 ^ (-1) = ~(-4) = ~1 . . . 100b = 0 . . . 011b = 3

Aha, so if number is negative it returns number - 1, then inverts all bits

$\Longrightarrow$ Two's complement!

So is branchless really faster?

Let's do a benchmark!

```
int Abs(int number)
{
    if (number >= 0) // condition
    {
        return number; // option 1
    }
    else
    {
        return number * (-1); // option 2
    }
}
```

```
int AbsBranchless(int number)
{
    int mask = (number >> 31);
    return (number + mask) ^ mask;
}
```

```
int BuiltInMathAbs(int number)
{
    return Math.Abs(number);
}
```

Benchmark results

Method	Mean	Error	StdDev	Ratio	RatioSD
`Abs`	18.110 us	0.2077 us	0.1943 us	1.00	0.00
`AbsBranchless`	6.995 us	0.1191 us	0.1114 us	0.39	0.01
`BuiltInMathAbs`	20.578 us	0.2992 us	0.2652 us	1.14	0.02

$\Longrightarrow$ `AbsBranchless()` is ~2.5 times faster (and more stable) than `Abs()` with branches!

Also: C# / .NET 7's `System.Math.Abs()` seems to be pretty slow

Branchless is just the beginning

Branchless programming translates conditional logic into arithmetic!
Can be further optimized using more advanced techniques:

- SIMD (Single instruction, multiple data) / vector arithmetic
- ILP (Instruction-Level-parallelism)
- GP-GPU (General purpose GPU computation)

Pitfalls, Do's and Dont's

Do

- **Do** always benchmark your changes
- **Do** consider using branchless code in low-level scenarios, such as
    - cryptography
    - audio / video processing
    - game development (i.e. physics simulations)
- **Do** consider eliminating branches in
    - tight loops
    - functions that are called very frequently
- **Do** always write comments!

Don't

- **Don't** just start optimizing code without a baseline benchmark.
- **Don't** be the guy writing branchless code in high-level scenarios, such as
    - database management
    - web request handling
    - a couple of microseconds won't matter...
- **Don't** write branchless code in places that must be maintained by multiple people or are changed frequently. Everyone will hate you...
- **Don't** assume your code is translated 1:1 into assembly. Always check what your compiler generates!
- **Don't** write branchless code in interpreted languages (JavaScript, Python, ...) it won't matter.

Useful in 1% of the cases

```
[MethodImpl(MethodImplOptions.AggressiveInlining)]
private static bool TryParseMpegHeader(void* pFrame)
{
    const uint FALSE = 0x0;
    const uint TRUE = ~FALSE;
    // extract frame header and inline buffer from pFrame
    Mp3FrameHeader* self = &((Mp3Frame*)pFrame)->Header;
    byte* pHeaderBytes = (byte*)pFrame;
    // assume success if nothing fails: (~0x0)
    int success = unchecked((int)TRUE);
    // load the MPEG version from the header
    MpegVersion mpegVersion = (MpegVersion)((pHeaderBytes[1] & 0b0001_1000u) >> 3);
    // if the mpegVersion is reserved (invalid) set success to FALSE (0x0)
    // use sign extension to convert to either 0x0 or ~0x0 (FALSE or TRUE)
    success &= (-(int)(mpegVersion ^ MpegVersion.Reserved)) >> 31;
    // determine the version index of the BitRates array using the mpegVersion.
    // if the mpegVersion is Version1 then the version index should be 0 otherwise it i
    // Enum member MpegVersion.Version1 has the value 3 (11 in binary).
    // any other possible value is 1 or 2 (01 or 10 in binary).
    // -> if both bits are equal (1 and 1) then the version index is 0 otherwise it is

    // -> first bit XOR second bit
    // if both bits are zero (0) then the success flag will be set to FALSE already and
    int versionIndex = ((int)mpegVersion & 0b01) ^ (((int)mpegVersion & 0b10) >> 1);
    // load the MPEG layer information from the header
```

```
    MpegLayer mpegLayer = (MpegLayer)((pHeaderBytes[1] & 0b0000_0110u) >> 1);
        ...
```

Questions?

... or a few moments of awkward silence. It's up to you 🤷

```
// secured my job :)
internal static bool IsValidMp3Header(void* pFrame) =>
    (unchecked((int)TRUE) & ((-(int)((MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3
    ) ^ MpegVersion.Reserved)) >> 31) & ((-(int)(MpegLayer)((((byte*)pFrame)[1] &
    0x06) >> 1)) >> 31) & (-((((byte*)pFrame)[2] & 0xF0) >> 4 ^ 15) >> 31) &
    (-BitRates[((int)(MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3) & 0b01) ^
    (((int)(MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3) & 0b10) >> 1), (int)
    (MpegLayer)((((byte*)pFrame)[1] & 0x06) >> 1), (((byte*)pFrame)[2] & 0xF0) >> 4
    ] >> 31) & (-((((byte*)pFrame)[2] & 0xF0) >> 4 ^ 3) >> 31) & (~((-(int)
    ((ChannelMode)((((byte*)pFrame)[3] & 0xC0) >> 6) ^ ChannelMode.JointStereo) >>
    31) & (-((((byte*)pFrame)[3] & 0x30) >> 4) >> 31))) & (~((MAX_FRAME_SIZE -
    ((((SamplesPerFrame[((int)(MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3) &
    0b01) ^ (((int)(MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3) & 0x2) >> 1),
    (int)(MpegLayer)((((byte*)pFrame)[1] & 0x06) >> 1)] >> 3) * BitRates[((int)
    (MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3) & 0x1) ^ (((int)(MpegVersion)
    ((((byte*)pFrame)[1] & 0x18) >> 3) & 0b10) >> 1), (int)(MpegLayer)((((byte*)
    pFrame)[1] & 0x06) >> 1), (((byte*)pFrame)[2] & 0xF0) >> 4] / SampleRates
    [(int)(MpegVersion)((((byte*)pFrame)[1] & 0x18) >> 3), (((byte*)pFrame)[2]
    & 0xC0) >> 2]) + ((((byte*)pFrame)[2] & 0x2) >> 1)) << (~(-(int)((MpegLayer)
    ((((byte*)pFrame)[1] & 0x06) >> 1) ^ MpegLayer.Layer1) >> 31) & 2))) >> 31)))
    == unchecked((int)TRUE);
```

"Documentation? Just read the code. The code: ... ⬆️ *"*