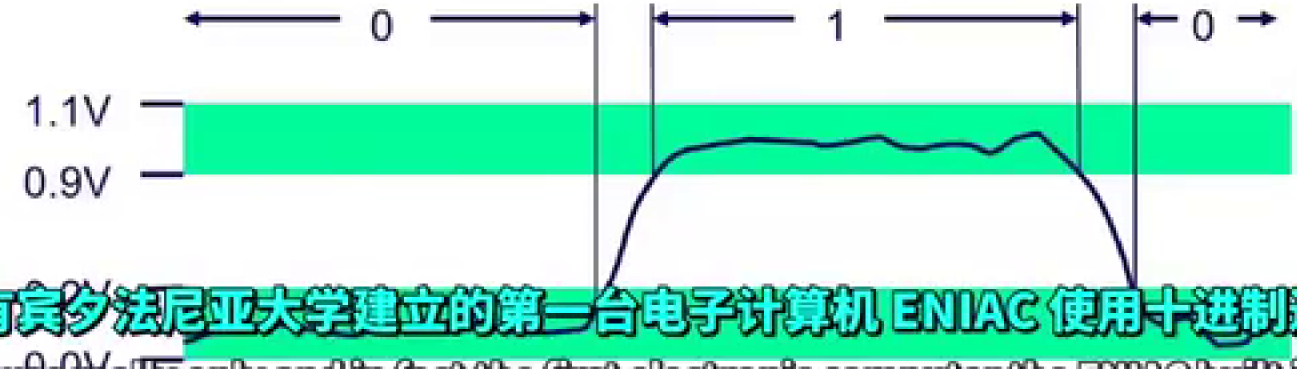
Everything is bits

- **Each bit is 0 or 1**
- **By encoding/interpreting sets of bits in various ways**
  - Computers determine what to do (instructions)
  - … and represent and manipulate numbers, sets, strings, etc…
- **Why bits? Electronic Implementation**
  - Easy to store with bistable elements
  - Reliably transmitted on noisy and inaccurate wires



实际上只有宾夕法尼亚大学建立的第一台电子计算机 ENIAC 使用十进制进行了算术运算

And it was really only and in fact the first electronic computer the ENIAC built in University of Pennsylvania basically encoded did all of its arithmetic using base ten

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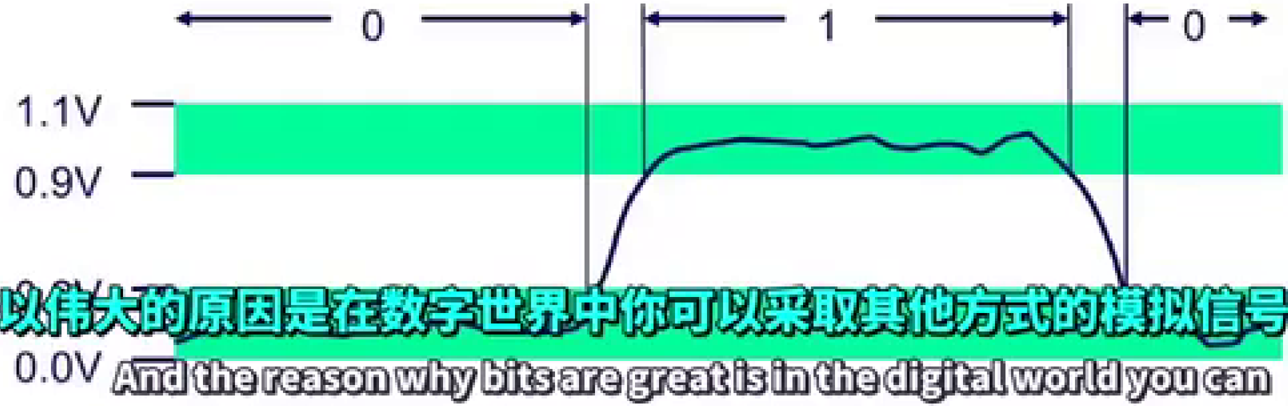

比特之所以伟大的原因是在数字世界中你可以采取其他方式的模拟信号对其进行量化

And the reason why bits are great is in the digital world you can sort of take what otherwise an analog signal and quantify it

For example, can count in binary

- **Base 2 Number Representation**
  - Represent 15213_{10} as 11101101101101_2
  - Represent 1.20_{10} as $1.0011001100110011[0011]\ldots_2$
  - Represent 1.5213×10^4 as $1.1101101101101_2 \times 2^{13}$

事实证明，存储一位信息或一个数字值比存储一个模拟值要容易得多

It turns out it's much easier to store one bit of information or a digital value than it is to store an analog value

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当我们处理浮点数时，我们要怎么处理小数点右边的数字

When we do floating-point numbers where what you do is to the right of the binary point

For example, can count in binary

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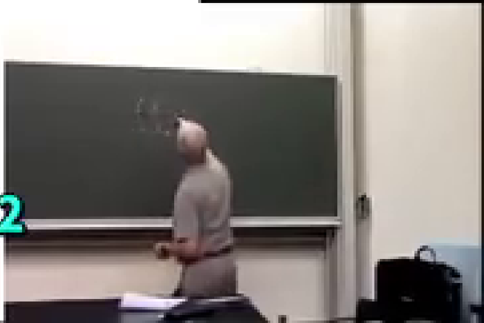


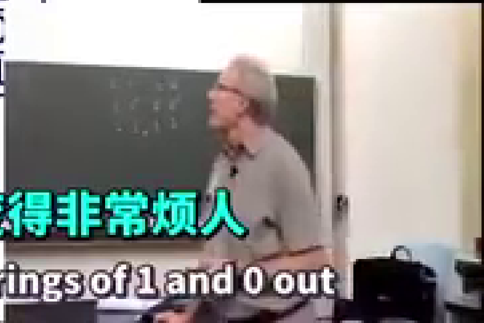
但是当你处理小数点右边的数字时它们增加的权重是 2^-1, 2^-2

But what you do is as you go to the right that adds weight 2^-1,2^-2

Encoding Byte Values

- **Byte = 8 bits**
  - Binary 00000000_2 to 11111111_2
  - Decimal: 0_{10} to 255_{10}
  - Hexadecimal 00_{16} to FF_{16}
    - Base 16 number representation
    - Use characters '0' to '9' and 'A' to 'F'
    - Write $FA1D37B_{16}$ in C as
      – 0xFA1D37B
      – 0xfa1d37b

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111



所以如果你见过数字写成 32 位甚至 64 位的 1 和 0 的字符串，那么它会变得非常烦人

And so it gets very annoying if you have say 32 or even 64-bit numbers to be writing the strings of 1 and 0 out

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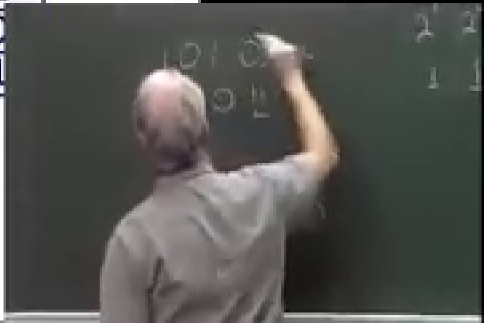
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111



Example Data Representations

C Data Type	Typical 32-bit	Typical 64-bit	x86-64
`char`	1	1	1
`short`	2	2	2
`int`	4	4	4
`long`	4	8	8
`float`	4	4	4
`double`	8	8	8
`long double`	–	–	10/16
pointer	4	8	8

实际上在大多数声明中你并不能被准确告知（变量有）多少字节

In most declarations you don't actually are told exactly how many bytes

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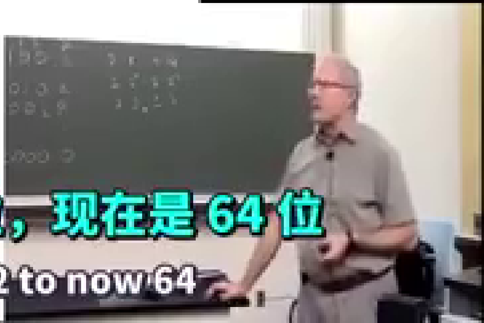

所以 16 位字长是一个相当的标准，随着时间的推移，它从 16 位扩展到 32 位，现在是 64 位

So 16-bit words were a fairly standard and over time that's expanded from 16 to 32 to now 64

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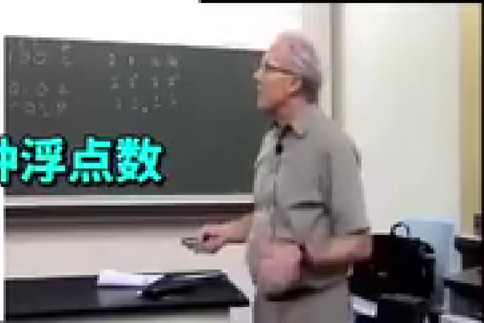

同样，浮点表示也有两种不同表示方法，4 个字节(32 位)和 64 位两种浮点数

And then again there's two different representations of floating-point
there's 4 byte or 32 bit of floating-point numbers and 64 bit

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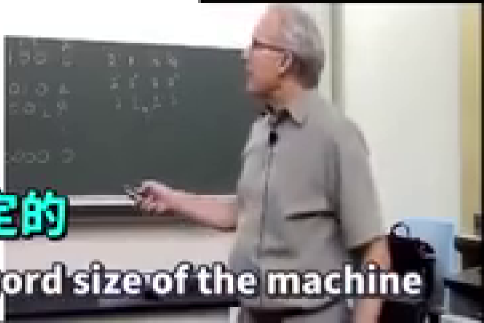

另一件事，这是一个重要的功能是虚拟地址空间是由机器字长决定的

The other thing and this is an important feature is any address is defined to be the sort of the word size of the machine

Boolean Algebra

- **Developed by George Boole in 19th Century**
  - Algebraic representation of logic
    - Encode "True" as 1 and "False" as 0

And

- **A&B = 1 when both A=1 and B=1**

&	0	1
0	0	0
1	0	1

Or

- **A|B = 1 when either A=1 or B=1**

|	0	1
0	0	1
1	1	1

Not

- **~A = 1 when A=0**

~	
0	1
1	0

Exclusive-Or (Xor)

- **A^B = 1 when either A=1 or B=1, but not b**

^	0	1
0	0	1
1	1	0

所以基础的事情是我们基于布尔代数来考虑位级运算

So the basis thing I imagine you've had this at some point of how do we then think about bits is based on boolean algebra

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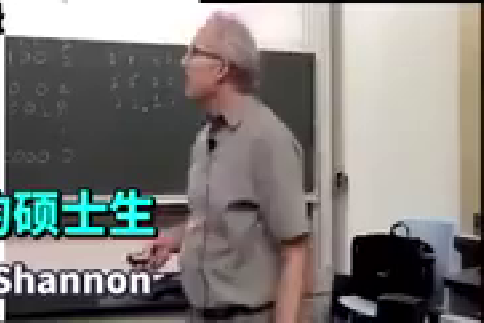


回顾比特的历史，它是麻省理工学院的一位名为 Claude Shannon 的硕士生

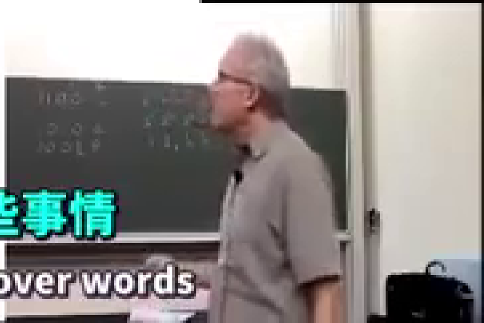
So just as a bit of history it was a master's degree student at MIT named Claude Shannon

General Boolean Algebras

- **Operate on Bit Vectors**
  - Operations applied bitwise

```
  01101001     01101001     01101001
& 01010101   | 01010101   ^ 01010101   ~ 01010101
  01000001     01111101     00111100     10101010
```

- **All of the Properties of Boolean Algebra Apply**

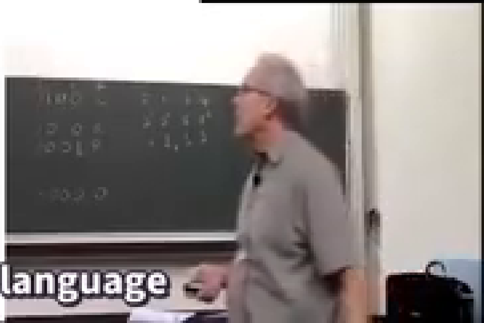


现在可能不那么明显的一件重要事情是，我们也可以用言语来做这些事情

Now what's an important thing that might be less obvious is we can also do these over words

Example: Representing & Manipulating Sets

- **Representation**
  - Width w bit vector represents subsets of {0, …, w–1}
  - $a_j = 1$ if $j \in A$
    - 01101001 { 0, 3, 5, 6 }
    - *76543210*
    - 01010101 { 0, 2, 4, 6 }
    - *76543210*
- **Operations**
  - & Intersection 01000001 { 0, 6 }
  - | Union 01111101 { 0, 2, 3, 4, 5, 6 }
  - ^ Symmetric difference 00111100 { 2, 3, 4, 5 }
  - ~ Complement 10101010 { 1, 3, 5, 7 }



你可以直接在语言中执行这些低级别的位操作

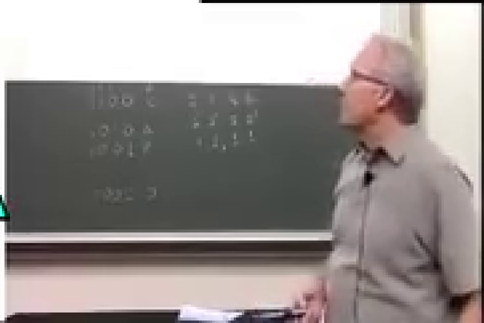
is that you can do these sort of very low level of bit manipulations directly in the language

Contrast: Logic Operations in C

- **Contrast to Logical Operators**
  - &&, ||, !
    - View 0 as "False"
    - Anything nonzero as "True"
    - Always return 0 or 1
    - Early termination
- **Examples (char data type)**
  - !0x41 → 0x00
  - !0x00 → 0x01
  - !!0x41 → 0x01
  - 0x69 && 0x55 → 0x01
  - 0x69 || 0x55 → 0x01
  - p && *p (avoids null pointer access)

所以我刚才提到那些可以直接在 C 语言中使用是&，|，～和 ^

so as I mentioned those are available directly in C the &,|, ~ and ^



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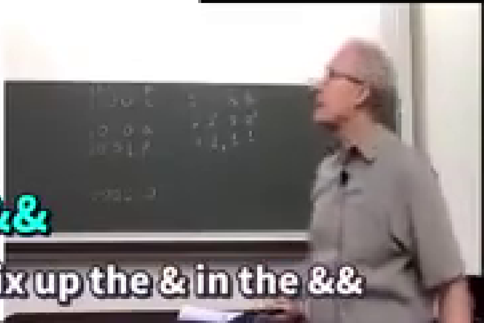

很多初级程序员，有时甚至是经验丰富的程序员都会混淆 & 在 &&

Beginning programmers a lot and even experienced programmers from time to time is to mix up the & in the &&

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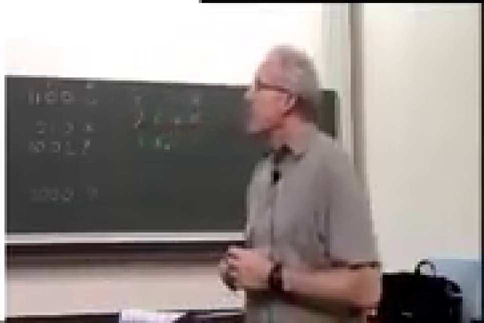

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  - 0x69 || 0x55 → 0x01
  - p && *p (avoids null pointer access)

如果这是 0 或 null，就能避免对 null 的引用

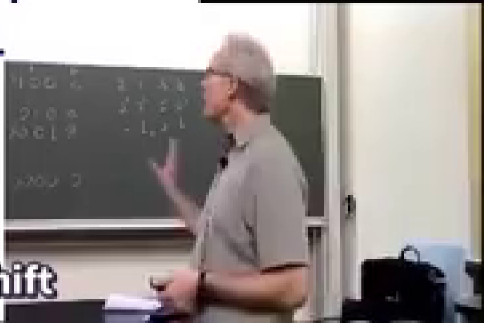
And this if this is 0 or null then it will do the the dereferencing of null

Shift Operations

- **Left Shift: x << y**
  - Shift bit-vector **x** left **y** positions
    - – Throw away extra bits on left
    - Fill with 0's on right
- **Right Shift: x >> y**
  - Shift bit-vector **x** right **y** positions
    - Throw away extra bits on right
  - Logical shift
    - Fill with 0's on left
  - Arithmetic shift
    - Replicate most significant bit on left
- **Undefined Behavior**
  - Shift amo

Argument x	01100010
<< 3	00010*000*
Log. >> 2	*00*011000
Arith. >> 2	*00*011000

Argument x	10100010
<< 3	00010*000*
Log. >> 2	*00*101000
Arith. >> 2	*11*101000



稍后我们会看到为什么有两种不同的右移方式

And we'll see in a little bit later why there's two different flavors of right shift

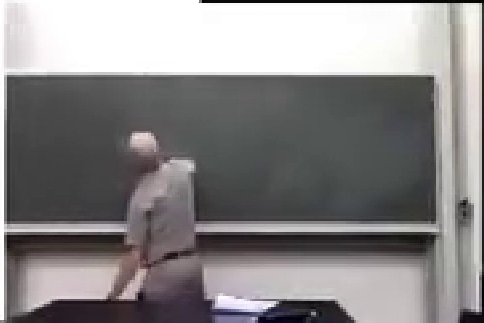
Numeric Ranges

- **Unsigned Values**
  - *UMin* = 0
    000…0
  - *UMax* = $2^w - 1$
    111…1

- **Two's Complement Values**
  - *TMin* = -2^{w-1}
    100…0
  - *TMax* = $2^{w-1} - 1$
    011…1
- **Other Values**
  - Minus 1
    111…1

Values for *W* = 16

	Decimal	Hex	Binary
UMax	65535	FF FF	11111111 11111111
TMax	32767	7F FF	01111111 11111111
TMin	-32768	80 00	10000000 00000000
-1	-1	FF FF	11111111 11111111
0	0	00 00	00000000 00000000



我将用一些例子来说明它

And I'm going to illustrate it with some examples

Encoding Integers

Unsigned

$$B2U(X) = \sum_{i=0}^{w-1} x_i \cdot 2^i$$

Two's Complement

$$B2T(X) = -x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i$$

Sign Bit

```
short int x =  15213;
short int y = -15213;
```

- C `short` 2 bytes long

	Decimal	Hex	Binary
`x`	15213	`3B 6D`	`00111011 01101101`
`y`	-15213	`C4 93`	`11000100 10010011`

- Sign Bit
  - For 2's complement, most significant bit indicates sign
    - 0 for nonnegative
    - 1 for negative

如果你有一个无符号的数字，那么这只是转换

If you have an unsigned number then this is just the conversion

Encoding Integers

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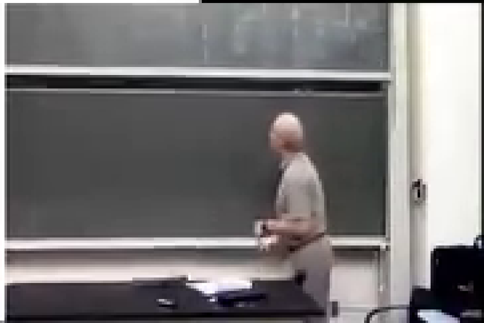
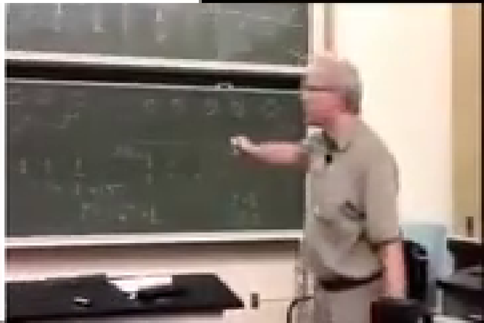


Values for Different Word Sizes

	W			
	8	16	32	64
UMax	255	65,535	4,294,967,295	18,446,744,073,709,551,615
TMax	127	32,767	2,147,483,647	9,223,372,036,854,775,807
TMin	-128	-32,768	-2,147,483,648	-9,223,372,036,854,775,808

- **Observations**
  - $|TMin| = TMax + 1$
    - Asymmetric range
  - $UMax = 2 * TMax + 1$
- **C Programming**
  - #include <limits.h>
  - Declares constants, e.g.,
    - ULONG_MAX
    - LONG_MAX
    - LONG_MIN
  - Values platform specific



这些数字中 UMax 最大的无符号数字

So these numbers I call UMax the biggest unsigned number

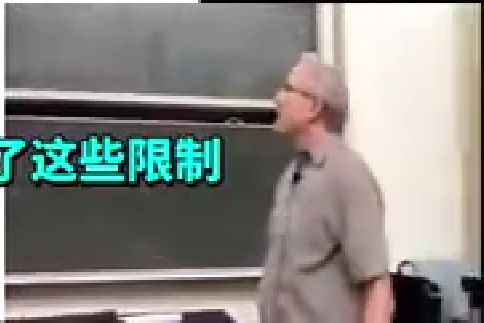
Unsigned & Signed Numeric Values

X	B2U(*X*)	B2T(*X*)
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	–8
1001	9	–7
1010	10	–6
1011	11	–5
1100	12	–4
1101	13	–3
[illegible]	[illegible]	[illegible]
1111	15	–1

- **Equivalence**
  - Same encodings for nonnegative values
- **Uniqueness**
  - Every bit pattern represents unique integer value
  - Each representable integer has unique bit encoding
- **⇒ Can Invert Mappings**
  - U2B(x) = B2U^{-1}(x)
    - Bit pattern for unsigned integer
  - T2B(x) = B2T^{-1}(x)
    - integer

但现在至少对我们来说，64 位数字看起来非常庞大，很难想象它们超出了这些限制

But now with 64 bits at least to us nowadays those seem like really big numbers and hard to imagine exceeding the bounds of those



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0110	6	6
0111	7	7
1000	8	–8
1001	9	–7
1010	10	–6
1011	11	–5
1100	12	–4
1101	13	–3
1110	14	–2
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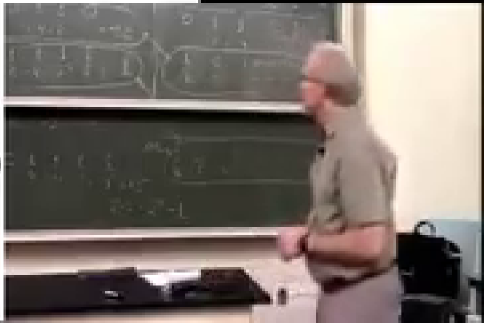
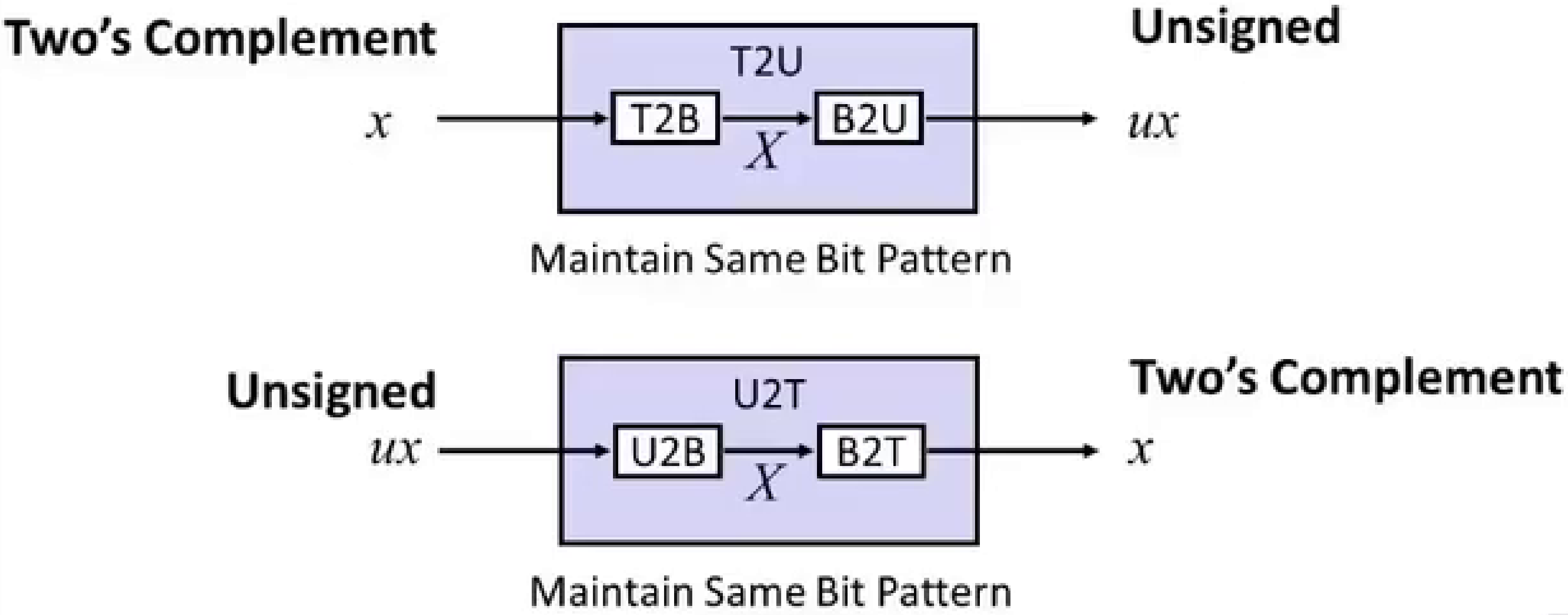


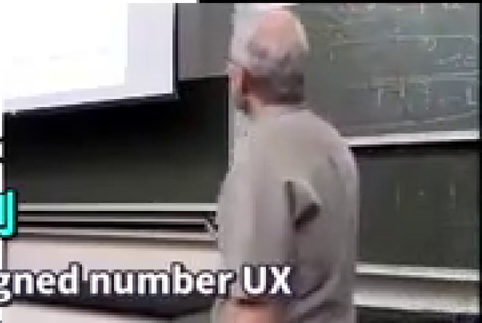
但是这种联系实际上相当重要

But that connection is actually fairly important

Mapping Between Signed & Unsigned



- Mappings between unsigned and two's complement numb

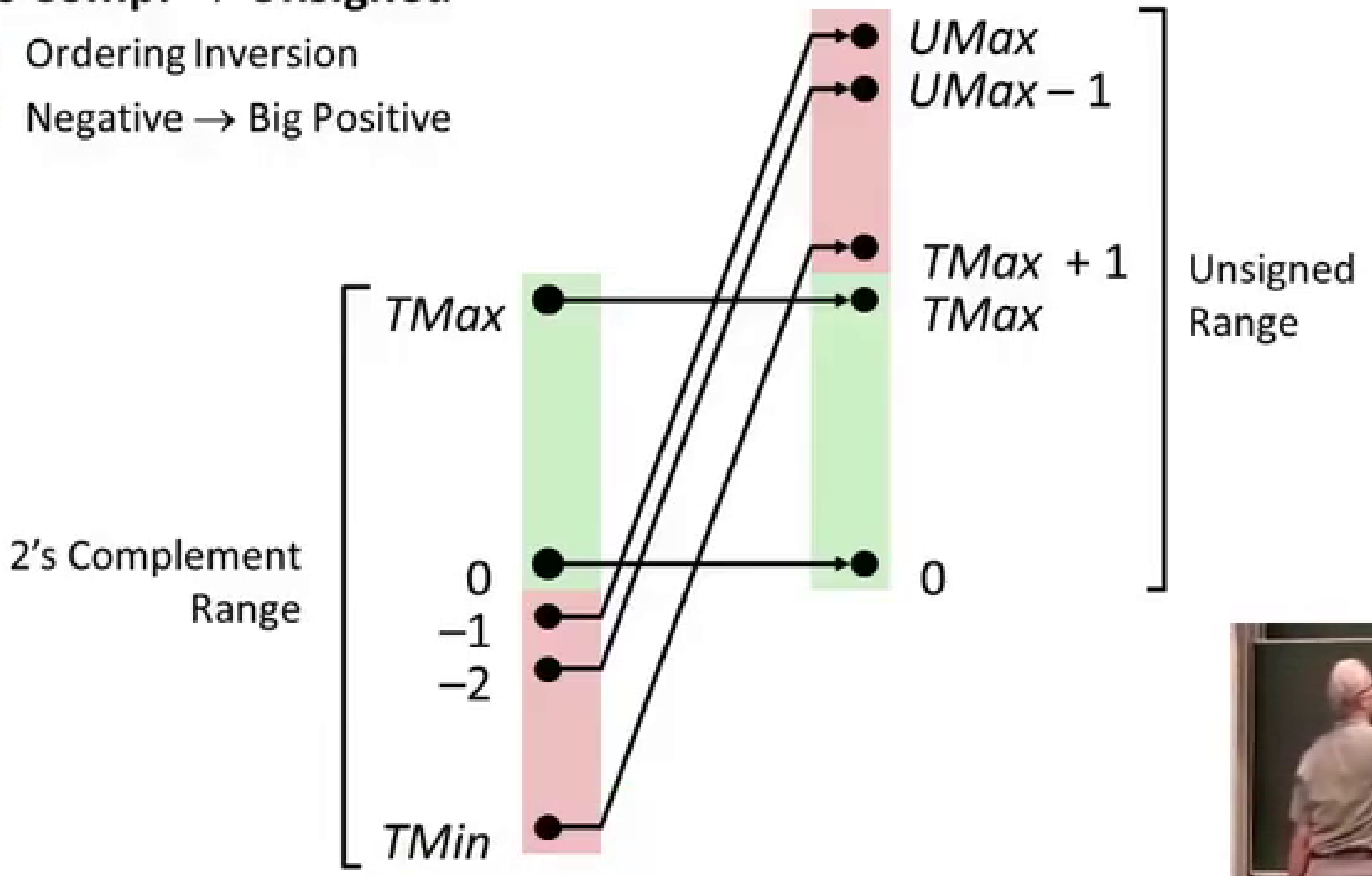


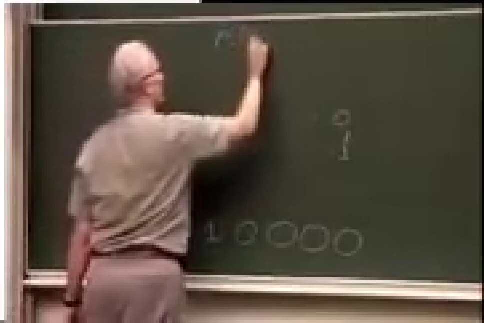
我可以定义一个在补码 X 和一个无符号数字 UX 之间转换的规则

I can make up a rule for converting between a two's complement number X and an unsigned number UX

Conversion Visualized

- **2's Comp. → Unsigned**
  - Ordering Inversion
  - Negative → Big Positive





Casting Surprises

- **Expression Evaluation**
  - If there is a mix of unsigned and signed in single expression, ***signed values implicitly cast to unsigned***
  - Including comparison operations <, >, ==, <=, >=
  - Examples for W = 32: **TMIN = -2,147,483,648 ,** **TMAX = 2,147,483,647**

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(unsigned)-1	-2	>	unsigned
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如果我看看两个数字，然后比较它们，或者实际上我会对它们进行一些操作

If I look at two numbers and I compare them or I actually I do any operation on them

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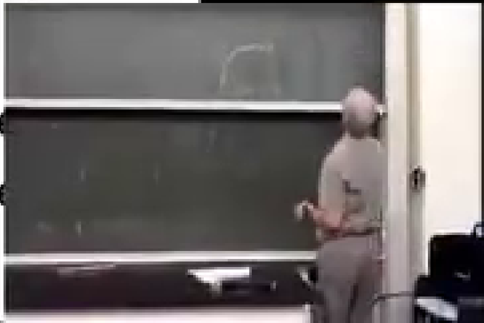

所以这是一个惊喜，它与我擦掉的一个数字有关

So this is the surprise and it has to do with...a number that I erased

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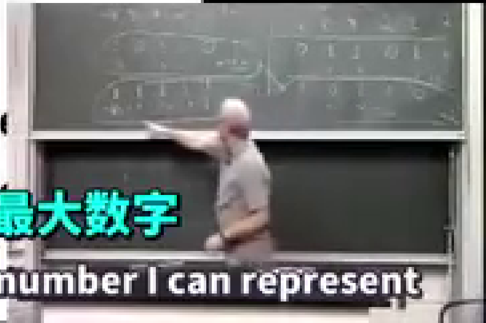

我把这个从 -16 改为 +16，并把它变成 31，我把它变成了我能代表的最大数字

I'm flipping this from -16 to +16 and turning this into 31 I'm turning it into actually the largest number I can represent

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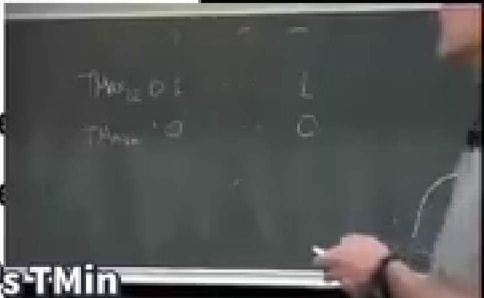

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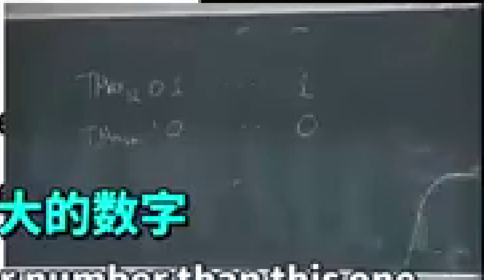

这个首位不是一个负权重，但一个正权重，你会看到这是一个比这个更大的数字

This leading bit not being a negative weight but a positive weight you'll see that this is a bigger number than this one

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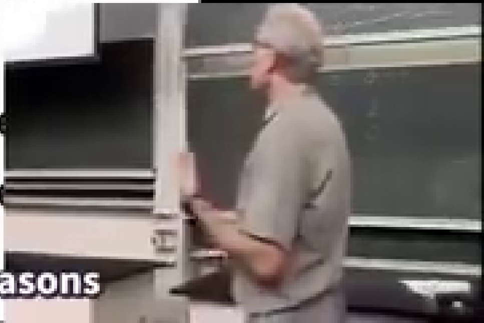

它实际上会让C编译器因为一些模糊的原因而感到困惑

It will actually get the C compiler gets kind of confused by that for obscure reasons

Casting Surprises

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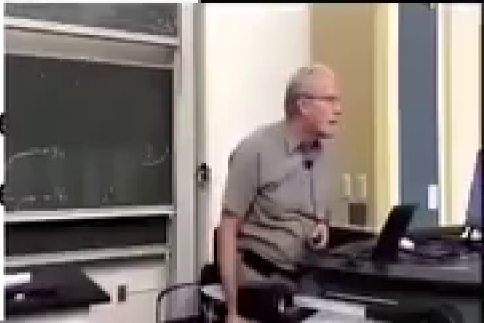

Summary
Casting Signed ↔ Unsigned: Basic Rules

- Bit pattern is maintained
- But reinterpreted
- Can have unexpected effects: adding or subtracting 2^w

- Expression containing signed and unsigned int
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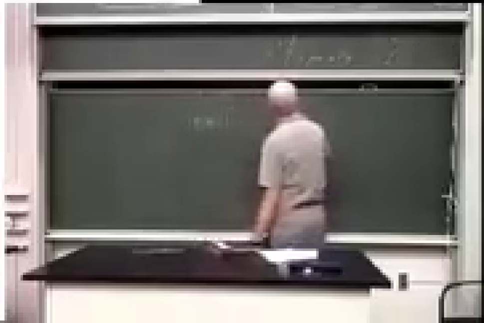

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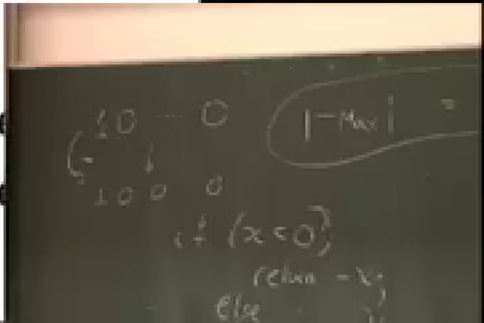

那么你说，哦，是大数字，但如何变成一个负数 - 是的

well that case you said oh yeah big number but how negative - one yes

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这确实是个问题，他们把括号括在里面，所以没有大的问题

It's exactly this problem and they put parentheses around it so there's no president's problem

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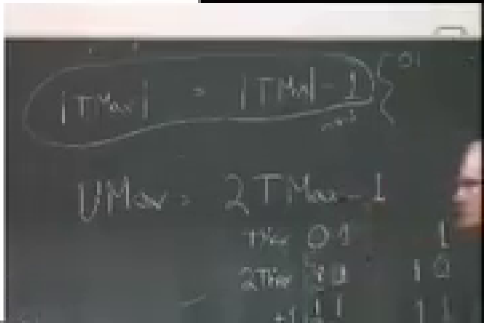

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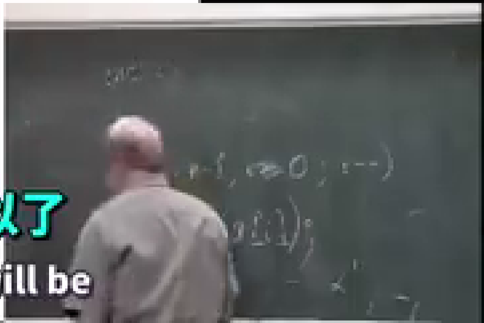

然后我们说一些事情，比如让我在这里稍微改变一下，这样就可以了

And then we say something like let me just change it here a little bit so this will be

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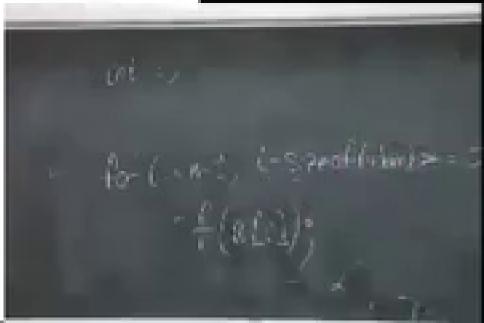
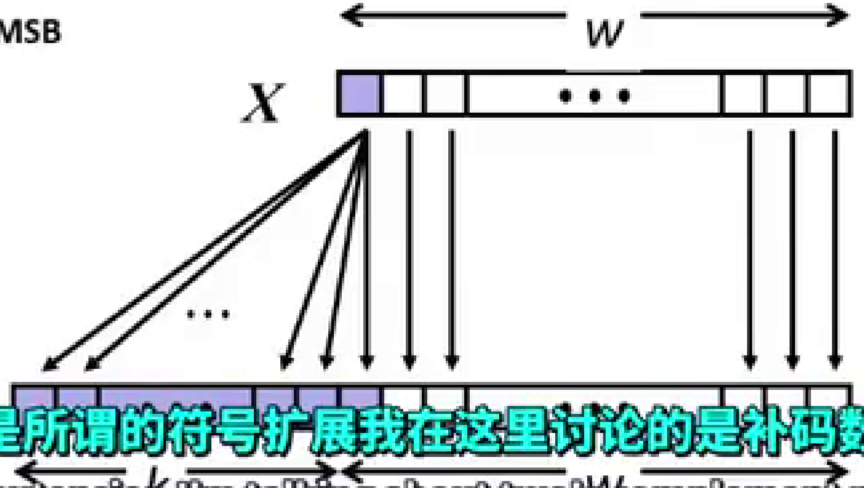
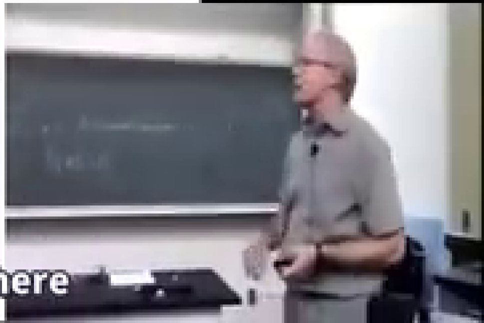


Sign Extension

- **Task:**
  - Given w-bit signed integer x
  - Convert it to $w+k$-bit integer with same value
- **Rule:**
  - Make k copies of sign bit:
  - $X' = \underbrace{x_{w-1}, \ldots, x_{w-1}}_{k \text{ copies of MSB}}, x_{w-1}, x_{w-2}, \ldots, x_0$





这就是所谓的符号扩展我在这里讨论的是补码数

That's called sign extension I'm talking about two's complement numbers here

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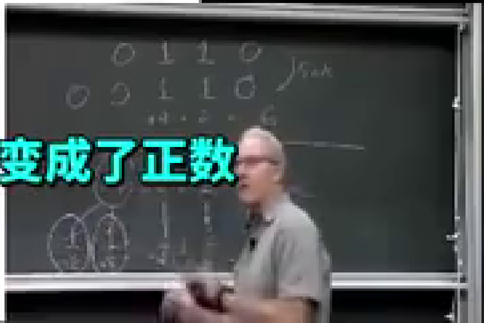
所以你通过复制这种符号的方式看到它给了它两倍的权重，把它的符号位变成了正数

So you see by sort of copying that sign bit over giving it twice the weight turning it what was the sign bit into a positive number



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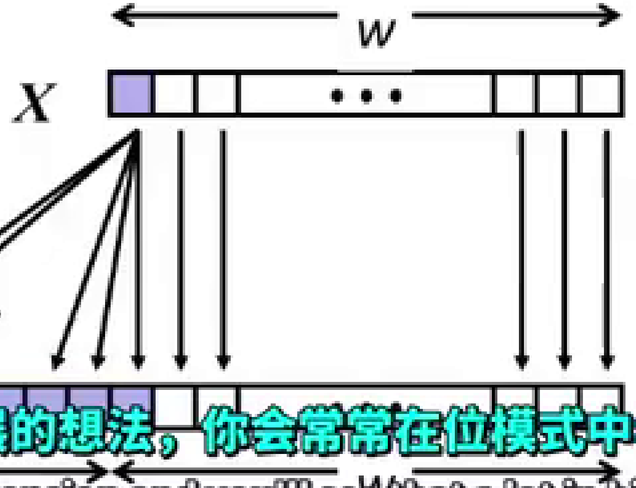
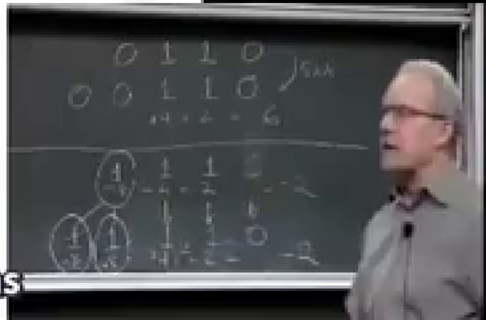




所以这就是符号扩展的想法，你会常常在位模式中看到

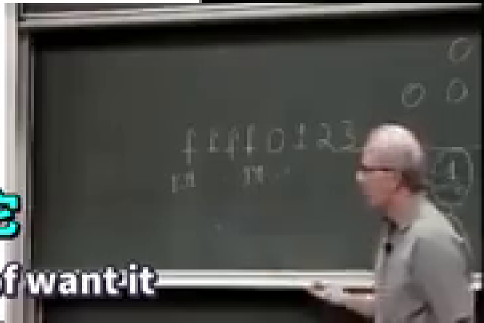
So that's the idea of sign extension and you'll see that a lot in bit patterns

Sign Extension Example

```
short int x =  15213;
int       ix = (int) x;
short int y = -15213;
int       iy = (int) y;
```

	Decimal	Hex	Binary
x	15213	3B 6D	00111011 01101101
ix	15213	00 00 3B 6D	00000000 00000000 00111011 01101101
y	-15213	C4 93	11000100 10010011
iy	-15213	FF FF C4 93	11111111 11111111 11000100 10010011

- Converting from smaller to larger integer data type
- C automatically performs sign extension



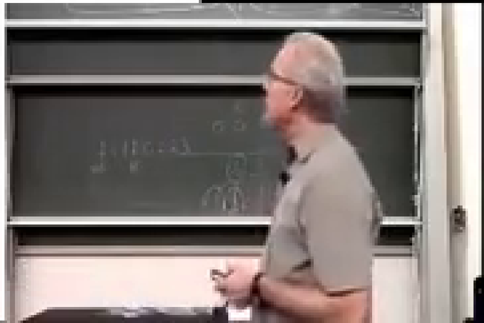
而且你会一遍又一遍地看到你会看到一些模式，而你只是想要它

And you'll see that over and over again you'll see bit patterns and you just sort of want it

Summary:
Expanding, Truncating: Basic Rules

- **Expanding (e.g., short int to int)**
  - Unsigned: zeros added
  - Signed: sign extension
  - Both yield expected result

- **Truncating (e.g., unsigned to unsigned short)**
  - Unsigned/signed: bits are truncated
  - Result reinterpreted
  - Unsigned: mod operation
  - Signed: similar to mod
  - For small numbers yields expected behavior



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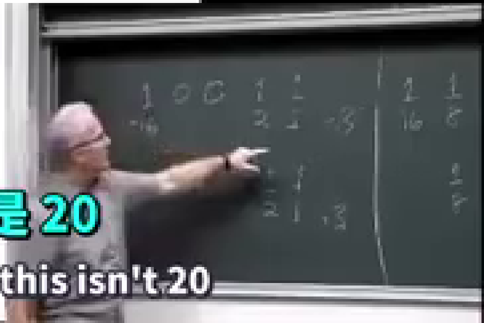

你知道这是 -13，但它有点像 27 和 27 模 16 有点像，或者，这不是 20

You know this is -13 but it's really kind of like 27 and 27 mod 16 is sort of like or,no this isn't 20

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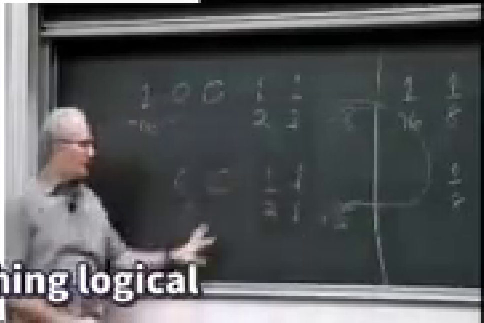

但它不是算术属性的总和，会跳出你的逻辑

But it's not sum of arithmetic property that would jump out at you as being something logical