To infinity – and beyond!

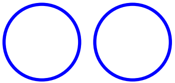
Julian Bradfield

School of Informatics
University of Edinburgh

Infinity and eternity

Infinity and eternity

for ever and ever (idiom)



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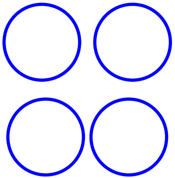

Infinity and eternity

for ever and ever (idiom)

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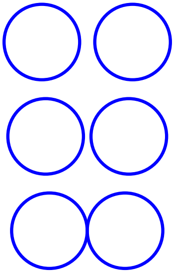

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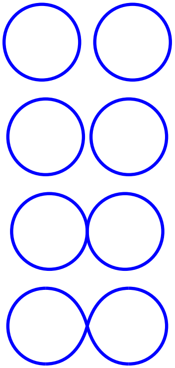
nunc et semper et in saecula saeculorum (from Greek, probably from Aramaic idiom)



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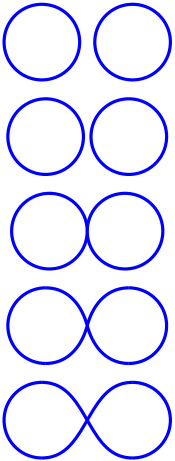
The King said, "The third question is, how many seconds of time are there in eternity." Then said the shepherd boy, "In Lower Pomerania is the Diamond Mountain, which is a league high, a league wide, and a league in depth; every hundred years a little bird comes and sharpens its beak on it, and when the whole mountain is worn away by this, then the first second of eternity will be over." (from Grimm)



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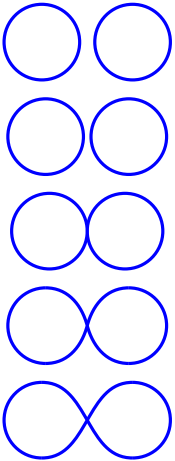
(from Grimm)

If the bird removes one atom each time, that's about 6×10^{40} years.



Towards infinity

Mathematicians and other children often play the following game: We take turns naming numbers, and see who can name the largest one. This is a game in the psychological rather than the formal sense, since I might always just add one to your number, but my goal is to try to completely demolish your ego by transcending your number via some completely new principle.

Kenneth Kunen
Handbook of Mathematical Logic

Guinness World Records / Tai Star Valianti

Georg Cantor

'The father of set theory'

1845–1918

Martin-Luther-Universität Halle-Wittenberg

1874: the birth of set theory, and the discovery of different levels of infinity

1883: the theory of ordinal numbers

Nobody shall drive us from the paradise that Cantor has created for us.

– David Hilbert

Ordinals and Cardinals

Language:

- cardinal numerals
  - *one*, *two*, ...
  - "how many?"
- ordinal numerals
  - *first*, *second*, ...
  - "where in a sequence?"

In Indonesian, numbers have cardinal meaning before the noun and ordinal after it. Some languages don't have ordinals at all.

Ordinals and Cardinals

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- cardinal numerals
  - *one*, *two*, . . .
  - "how many?"
- ordinal numerals
  - *first*, *second*, . . .
  - "where in a sequence?"

Mathematics:

- cardinal numbers
  - 0, 1, 2, . . .
  - "how many [in a set]?"
- ordinal numbers
  - 0, 1, 2, . . .
  - "where in a sequence?", also "how long [is a sequence]?"

The sequence a, b, a is 3 letters long, but contains 2 distinct letters.

In Indonesian, numbers have cardinal meaning before the noun and ordinal after it. Some languages don't have ordinals at all.

Counting

0:

1: |

2: ||

10: ||||||||||

Counting

0:

1: |

2: ||

10: ||||||||||

Obviously we can keep counting ‘for ever’:

|||||||||||||||||||| •••

Counting

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and why not count ‘for ever and a day’?

|||||||||||||||||||| ••• |

Counting

0:

1: |

2: ||

10: ||||||||||

Obviously we can keep counting 'for ever':

ω: |||||||||||||||||||| •••

and why not count 'for ever and a day'?

$\omega + 1$: |||||||||||||||||||| ••• |

Write ω for the length of the infinite sequence.

Counting

0:

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$\omega + 1$: |||||||||||||||||||| ••• |

Write ω for the length of the infinite sequence.

To help visualization, compress the infinite sequence to

|||.

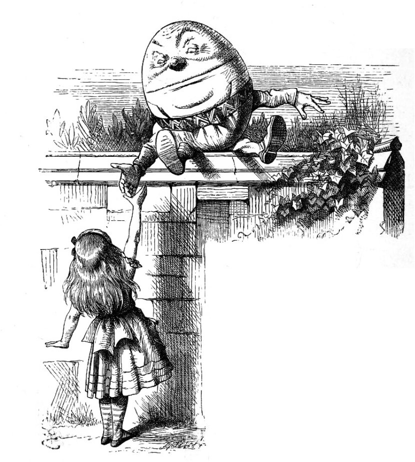
Addition of ordinals

Adding sequences is just putting one after the other:

$\omega + 1$: ‘for ever and a day’

$\omega + 3$:

$\omega + \omega$: ‘for ever and ever’



Sir John Tenniel

Addition of ordinals

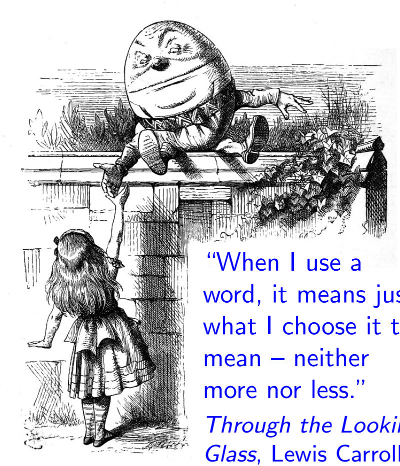
Adding sequences is just putting one after the other:

$\omega + 1$: 'for ever and a day'

$\omega + 3$:

$\omega + \omega$: 'for ever and ever'

But $1 + \omega$: $= \omega$



"When I use a word, it means just what I choose it to mean – neither more nor less."

Through the Looking Glass, Lewis Carroll

Sir John Tenniel

Multiplication of ordinals

Integer multiplication is just repeated addition: $2 \times 3 = 2 + 2 + 2$.

By convention, let's write $x \cdot y$ to mean y copies of x added together.

$2 \cdot 3$: || || ||

$\omega \cdot 3$:

$2 \cdot \omega$: || || $\bullet\bullet\bullet$ $=$ $= \omega$

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$2 \cdot \omega$: || || ••• $=$ |||. $= \omega$

$\omega \cdot \omega$: |||.|||.|||. ••• 'in saecula saeculorum'

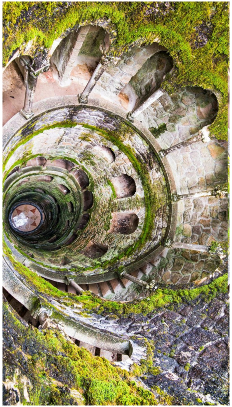
which we might visualize as

"the Multiplication Table doesn't signify"
Alice in Wonderland, Lewis Carroll

Sir John Tenniel

Well-foundedness and induction

The fundamental property of ordinals: they are *well-founded*. If you jump from an ordinal to any smaller ordinal, and keep doing that, then after a **finite** (but arbitrarily large) number of steps, you will hit zero.



Inverted tower of Sintra ©BBC

Well-foundedness and induction

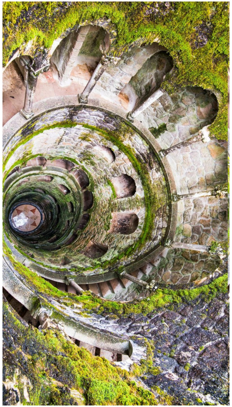
The fundamental property of ordinals: they are *well-founded*. If you jump from an ordinal to any smaller ordinal, and keep doing that, then after a **finite** (but arbitrarily large) number of steps, you will hit zero.

This means that ordinals can generalize *proof by induction*:

If

- $P(\alpha)$ holds for $\alpha = 0$, and
- **if** $P(\beta)$ holds for all $\beta < \alpha$, **then** $P(\alpha)$ holds,

then we can conclude that $P(\alpha)$ holds for all ordinals α.



Inverted tower of Sintra ©BBC

Example: why does Ackermann terminate?

The *Ackermann* function (of two integer arguments) $A(x, y)$ is defined recursively thus:

$$
\begin{aligned}
A(0, y) &= y + 1 \\
A(x, 0) &= A(x - 1, 1) && \text{for } x > 0 \\
A(x, y) &= A(x - 1, A(x, y - 1)) && \text{for } x, y > 0
\end{aligned}
$$

Wilhelm Ackermann

Is it obvious that this recursive computation ever finishes on, e.g., $A(4, 4)$?
$A(4, 4) = A(3, A(4, 3)) = A(3, A(3, A(4, 2))) = \ldots$

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$A(4, 4) = A(3, A(4, 3)) = A(3, A(3, A(4, 2))) = \ldots$

In each recursive call, *either* x gets smaller, *or* x stays the same and y gets smaller.

This is an induction on $\omega \cdot \omega$.

The Ackermann function grows quite fast – see later ...

Powers of Ordinals

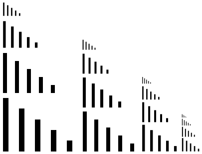
Integer exponentiation is just repeated multiplication:
$2^3 = 2 \times 2 \times 2$.

I.e., we write x^y for y copies of x multiplied together.

ω^2: $\omega \cdot \omega$

2^ω: $2 \cdot 2 \cdot 2 \cdot \ldots = \omega$

ω^3: $\omega \cdot \omega \cdot \omega = \omega^2 \cdot \omega$



The greatest shortcoming of the human race is our inability to understand the exponential function.
– Albert A. Bartlett

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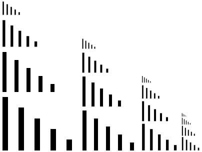
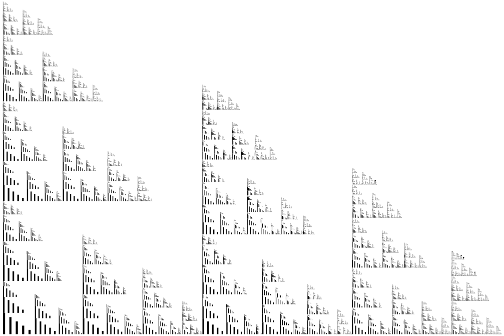
ω^3: $\omega \cdot \omega \cdot \omega = \omega^2 \cdot \omega$



ω^ω: $\omega \cdot \omega \cdot \omega \cdot \ldots$



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A little puzzle . . .

A number is written in *hereditary base* b if it's a sum of powers of b, with all the exponents also written in hereditary base b. E.g. with $b = 2$

$$1030 = 2^{10} + 2^2 + 2 = 2^{2^{2+1}+2} + 2^2 + 2$$

or with $b = 3$

$$1030 = 3^{3+3} + 3^{3+1+1} + 3^3 + 3^3 + 3 + 1$$

R. Louis Goodstein

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R. Louis Goodstein

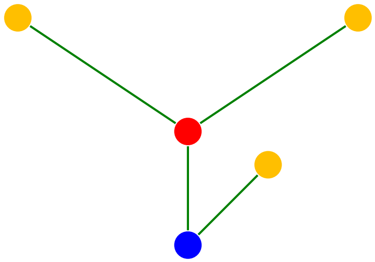
Think of a number n. Write it in h.b. 2. Now replace 2 by 3 and evaluate. Subtract 1. Write the result in h.b. 3. Replace 3 by 4 and evaluate. Subtract 1. And so on ... until you hit zero.

Let $G(n)$ be the length of this process – if it finishes!

For example: $G(3)$

$3 =_2 2 + 1$

A magic money tree



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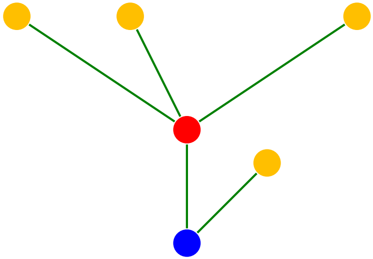
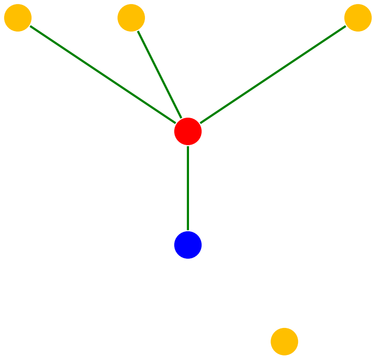


For example: $G(3)$

$$3 =_2 2 + 1$$
$$\rightarrow \quad 3 + 1 =_3 4$$
$$4 - 1 = 3 =_3 3$$

A magic money tree



For example: $G(3)$

$$\begin{aligned} 3 &=_2 2+1 \\ &\to \; 3+1 =_3 4 \\ 4-1 = 3 &=_3 3 \\ &\to \; 4 \quad =_4 4 \end{aligned}$$

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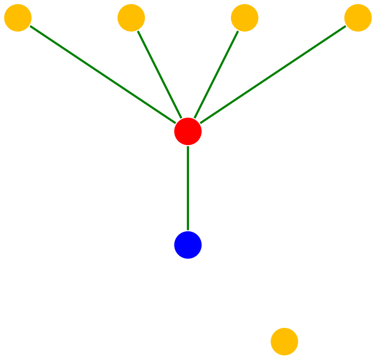

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$$\begin{aligned} 3 &=_2 2+1 \\ &\to\ 3+1 =_3 4 \\ 4-1 = 3 &=_3 3 \\ &\to\ 4 \quad\ \ =_4 4 \\ 4-1 = 3 &=_4 3 \end{aligned}$$

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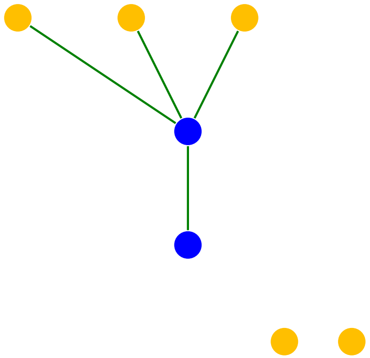
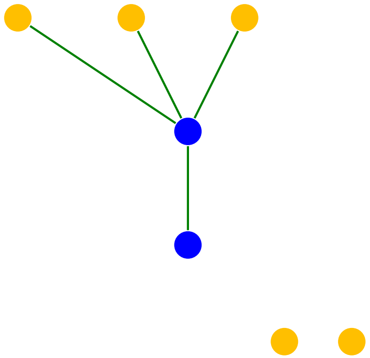


For example: $G(3)$

$$\begin{aligned}
& 3 =_2 2 + 1 \\
& \to \quad 3 + 1 =_3 4 \\
4 - 1 = {} & 3 =_3 3 \\
& \to \quad 4 \qquad =_4 4 \\
4 - 1 = {} & 3 =_4 3 \\
& \to \quad 3 \qquad =_5 3
\end{aligned}$$

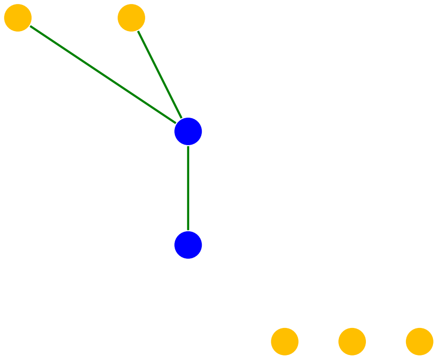
A magic money tree



For example: $G(3)$

$$
\begin{aligned}
& & 3 &=_2 2+1 & & \\
& & &\to \quad 3+1 &=_3 & \; 4 \\
4-1 &= & 3 &=_3 3 & & \\
& & &\to \quad 4 &=_4 & \; 4 \\
4-1 &= & 3 &=_4 3 & & \\
& & &\to \quad 3 &=_5 & \; 3 \\
3-1 &= & 2 &=_5 2 & &
\end{aligned}
$$

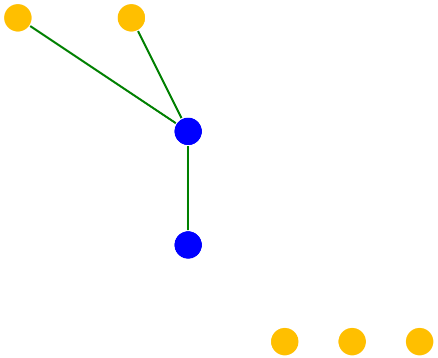
A magic money tree



For example: $G(3)$

$$
\begin{aligned}
3 &=_2 2 + 1 \\
&\to 3 + 1 =_3 4 \\
4 - 1 = 3 &=_3 3 \\
&\to 4 \qquad =_4 4 \\
4 - 1 = 3 &=_4 3 \\
&\to 3 \qquad =_5 3 \\
3 - 1 = 2 &=_5 2 \\
&\to 2 \qquad =_6 2
\end{aligned}
$$

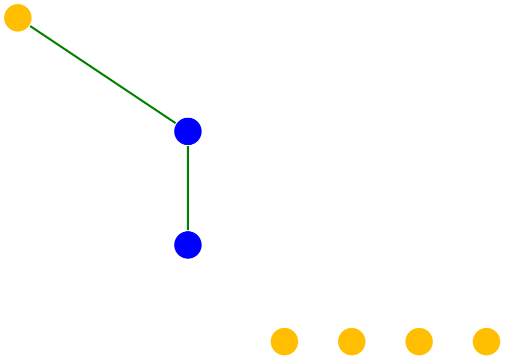
A magic money tree



For example: $G(3)$

$$
\begin{aligned}
& & 3 &=_2 2+1 & & \\
& & \rightarrow\ & \ 3+1 &=_3 & 4 \\
4-1 &= 3 &=_3 & 3 & & \\
& & \rightarrow\ & \ 4 &=_4 & 4 \\
4-1 &= 3 &=_4 & 3 & & \\
& & \rightarrow\ & \ 3 &=_5 & 3 \\
3-1 &= 2 &=_5 & 2 & & \\
& & \rightarrow\ & \ 2 &=_6 & 2 \\
2-1 &= 1 &=_6 & 1 & &
\end{aligned}
$$

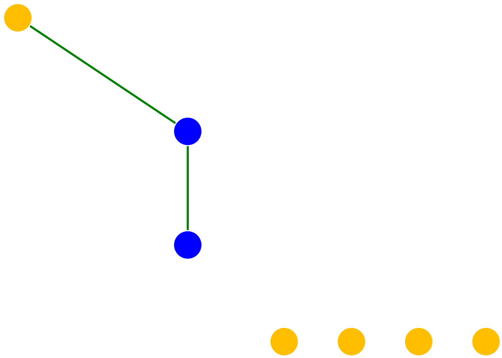
A magic money tree



For example: $G(3)$

$$
\begin{array}{rcll}
 & & 3 =_2 2+1 & \\
 & \to & 3+1 & =_3 4 \\
4-1 = 3 & =_3 & 3 & \\
 & \to & 4 & =_4 4 \\
4-1 = 3 & =_4 & 3 & \\
 & \to & 3 & =_5 3 \\
3-1 = 2 & =_5 & 2 & \\
 & \to & 2 & =_6 2 \\
2-1 = 1 & =_6 & 1 & \\
 & \to & 1 & =_7 1
\end{array}
$$

A magic money tree



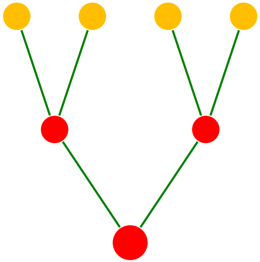
For example: $G(3)$

$$
\begin{aligned}
& & 3 &=_2 2+1 & & \\
& & &\to\ 3+1 &=_3& 4 \\
4-1 &= 3 &=_3& 3 & & \\
& & &\to\ 4 &=_4& 4 \\
4-1 &= 3 &=_4& 3 & & \\
& & &\to\ 3 &=_5& 3 \\
3-1 &= 2 &=_5& 2 & & \\
& & &\to\ 2 &=_6& 2 \\
2-1 &= 1 &=_6& 1 & & \\
& & &\to\ 1 &=_7& 1 \\
1-1 &= 0 & & & &
\end{aligned}
$$

So $G(3) = 6$

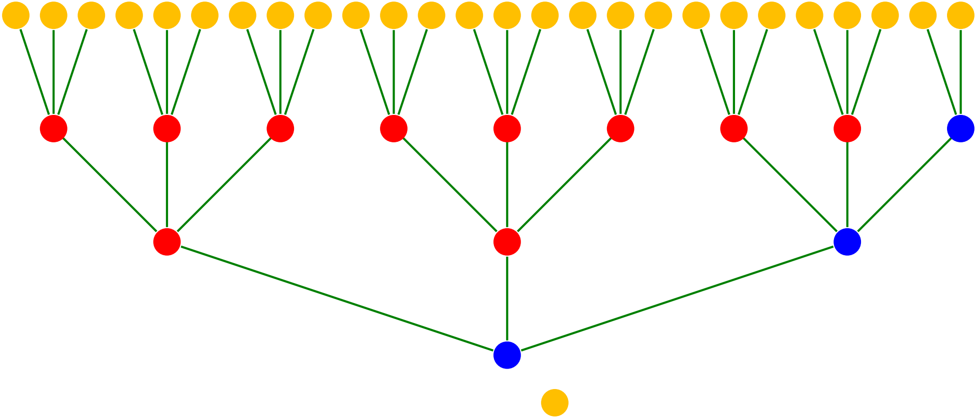
A magic money tree

The $G(4)$ magic money tree



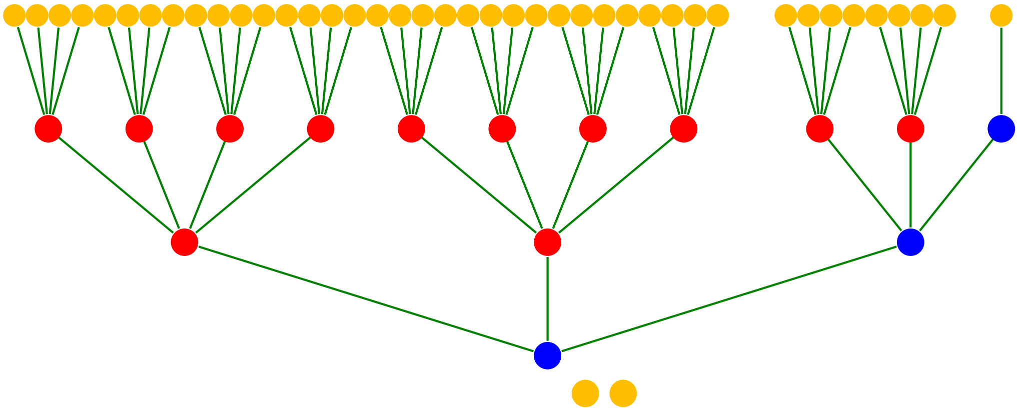
$4 = 2^2$

The $G(4)$ magic money tree



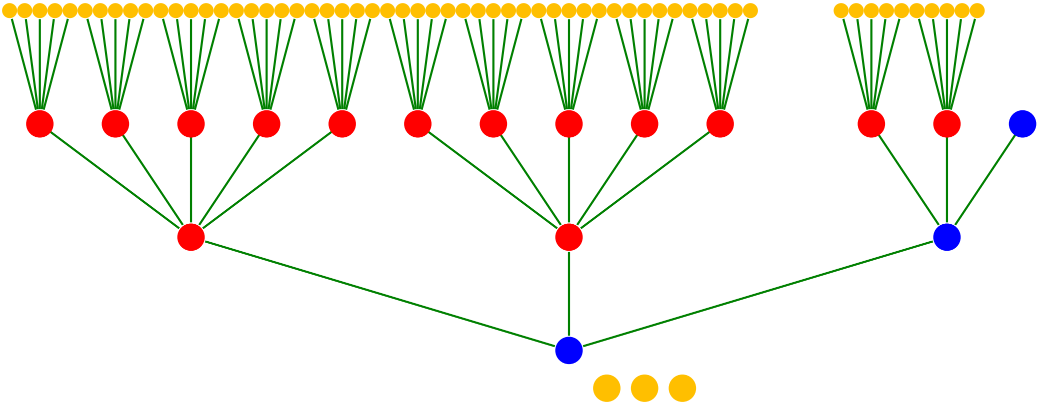
$26 = 3^2 + 3^2 + 3 + 3 + 2$

The $G(4)$ magic money tree



$41 = 4^2 + 4^2 + 4 + 4 + 1$

The $G(4)$ magic money tree



$60 = 5^2 + 5^2 + 5 + 5$

$G(4) = \infty$?

$G(4) =$

68950808030926201657363899596115099569577498758029736589
65164942362743495979724871888253075446277672715412687741
34196294274754024623945165423420847416977379911463833552
69129320073235045130731133415321473276443100557449932505
15006661770697335697266822986380629230539311939473732984
32189645058087369473177341975229512418408401173732994662
36583517126642762404390343968364036246706786021125426974
22457548590135058038973996050222167215602290558339854433
64582849621578912386681708820717886170299010486094304298
31938313300623537993032219144244347215613123094143176938
67571586750377935644459245645595556087522305546773436198
47032332425407785083961078958596196387897297104581844575
77157677751206967346327625413465613506947655384380307508
65233130216216163628621847422406626611936799943353915562
43559138950800725078317787807770746695975268954544726471
50035241859874391011058882911482099143475541850986185545

There are 896 digits on this page. They were computed with a small C program.

We now skip 135278 slides . . .

The skipped 121209088 digits were computed too. It takes less than a minute. They were *not* computed by counting the length of the sequence!

30187441025940056292813034386280177679544034517464936619
31073504178981468557969472279965424657699404235005937914
72930883993663027161466688743717253581936410274739801296
83060714286243899305063868650864112105238061406944808189
08304913462509086531545100380965533413343423478836091833
53220182680722735478679352859535040769913825815484931187
10726329608316620305483302616305150324000876272357296528
10182401729583610978448023254665651115973448118179302336
79234929512268465106495927833854484067484182464486747555
62975216019453924341023727286959093404563639409013246678
20328593203290715635768149137536972887886088038810819894
08291784060416318863529224353808259669206267357619658951
446422310193135419323844928197722374143

The actual sum done was $2^{24 \cdot 2^{24}} \cdot 2^{24} \cdot 24 - 1$

Or, more comprehensibly, about 7×10^{121210694}; or about $2^{2^{29}}$.

$G(5) \simeq$

$$10^{10^{\cdot^{\cdot^{\cdot^{10}}}}}$$

$G(5) \simeq$

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Very much larger numbers occur as upper bounds to problems in graph theory, e.g. *Graham's number*

or to put it in binary,

$$\left. 2^{2^{\cdot^{\cdot^{\cdot^{2}}}}} \right\} \left. 2^{2^{\cdot^{\cdot^{\cdot^{2}}}}} \right\} \left. 2^{2^{\cdot^{\cdot^{\cdot^{2}}}}} \right\} 2^{2^{2^{2^{6}}}}$$

Why does G always terminate?

A slight variation of the description:

Think of a number n. Write it in h.b. 2, and replace 2 by ω; let $b = 2$. Increment b, and subtract 1, expanding ω to b (only) when necessary; repeat until zero.

$$\begin{array}{rll}
4 &= \omega^\omega & b = 2 \\
\to 26 &= \omega^\omega - 1 & b = 3 \\
&= \omega^3 - 1 & b = 3 \\
&= \omega^2 + \omega^2 + \omega^2 - 1 & b = 3 \\
&= \omega^2 + \omega^2 + \omega + \omega + \omega - 1 & b = 3 \\
&= \omega^2 + \omega^2 + \omega + \omega + 2 & b = 3 \\
\to 41 &= \omega^2 \cdot 2 + \omega \cdot 2 + 1 & b = 4 \\
\to 60 &= \omega^2 \cdot 2 + \omega \cdot 2 & b = 5 \\
\to 83 &= \omega^2 \cdot 2 + \omega + 5 & b = 6
\end{array}$$

The ordinal always decreases, even while its evaluation with $\omega = b$ is increasing. This is ordinal induction.

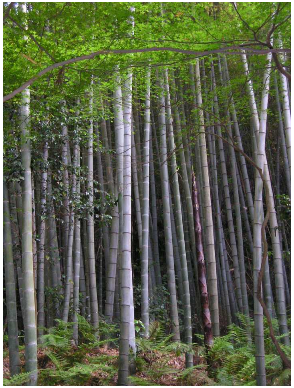
This works even if we multiply b by a million each step, not just add 1 to it.

Fast-growing functions . . .

$G(n)$ grows fast. So also does Ackermann $A(x, y)$:

$x \backslash y$	0	1	2	3	4
0	1	2	3	4	5
1	2	3	4	5	6
2	3	5	7	9	11
3	5	13	29	61	125

Some bamboos grow at 90cm/day



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4	13	65533	$\sim 2^{65533}$	$\sim 2^{2^{65533}}$	$\sim 2^{2^{2^{65533}}}$

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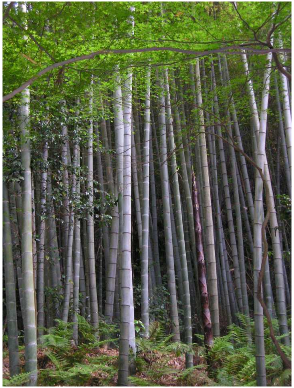

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Let $A(n)$ mean $A(n, n)$. It looks as if $A(n) > G(n)$:

n	$A(n)$	$G(n)$
0	1	1
1	3	2
2	7	4
3	61	6
4	$2^{2^{2^{65533}}}$	$2^{2^{29}}$

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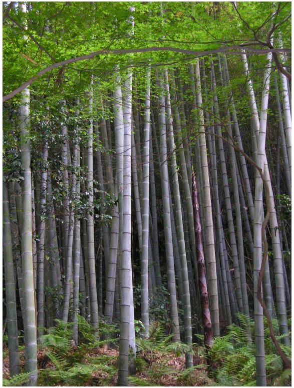
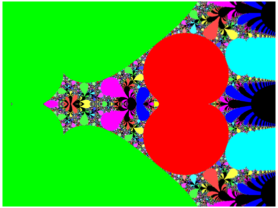


. . . via iterating exponentiation . . .

Multiplication $2 \cdot n$ is iterated addition $2 + 2 + 2 + \cdots + 2$.

Exponentiation 2^n or $2\hat{\ }n$ is iterated multiplication $2 \times 2 \times 2 \times \cdots \times 2$.

Iterated exponentiation can also be applied to complex numbers, where it gives rise to Mandelbrot-like patterns



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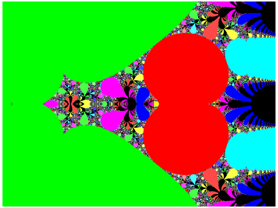

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Call a number *small* if it's . . . small . . .

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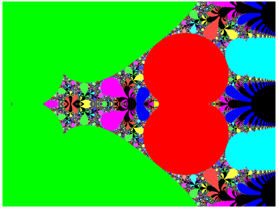

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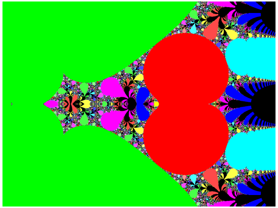

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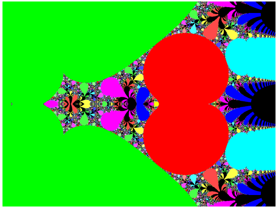

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Let's continue the Ackermann – Goodstein comparison:

n	$A(n)$	$G(n)$
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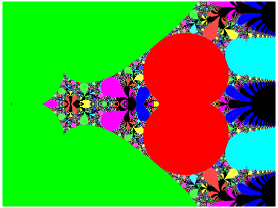

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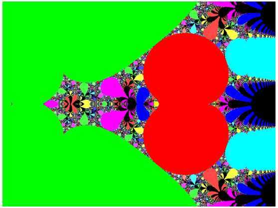

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7	5-big	7-big
8	6-big	$G(4)$-big

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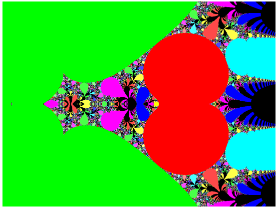

. . . and so *ad infinitum*

Call a number *1-huge* if it's (1-big)-big, *2-huge* if it's (1-huge)-big, etc.

These are not real mathematical definitions! But they are modelled on real definitions used in 'large cardinal' theory, which deals with *serious* infinities.

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Call a number *1-huge* if it's (1-big)-big, *2-huge* if it's (1-huge)-big, etc.

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etc. etc. etc. etc. till your brain explodes.

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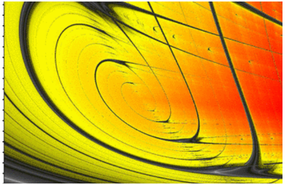
We can iterate exponentiation on ordinals . . . for ever and ever!

$$\omega, \omega^{\omega}, \omega^{\omega^{\omega}}, \ldots$$

Let $\epsilon_0 = \omega\hat{}\hat{}\omega = \omega^{\omega^{\omega^{\cdot^{\cdot^{\cdot}}}}}$

Note that $\omega^{\epsilon_0} = \epsilon_0$.



Periodicity Hub and Nested Spirals in the Phase Diagram of a Simple Resistive Circuit,
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Phys.Rev.Let. 054101 (2008)

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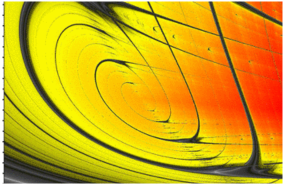

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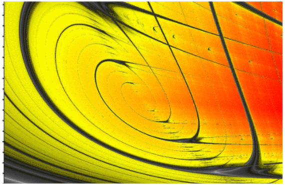

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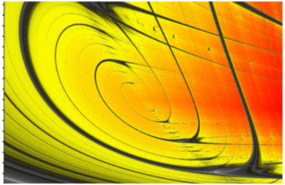

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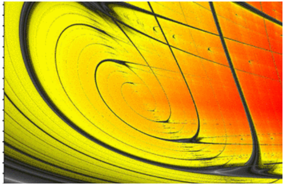
Then start counting fixed points of the functions that list the fixed points: the *Veblen* hierarchy. The end of this process is called Γ_0.



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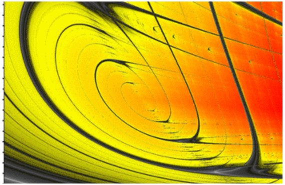
Then it starts getting complicated . . .



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Why do (some) computer scientists care?

The working theoretical computer scientist needs ordinals to do inductions. However, generally speaking, up to ω^ω is as far as we need to go.

Proof theorists (logicians, but sometimes found in CS depts!) need much bigger ordinals.

The strength of a theory (how much that is true, can it prove?) can be measured by how long are the inductions it can do.

E.g. *Primitive Recursive Arithmetic* can't do ω^ω inductions.

Peano Arithmetic can't do ϵ_0 induction – so can't prove that G terminates!

Proof Theory may be of interest to *Theorem Provers* . . .

Envoi

All these ordinals are small!

The real Cantorian revolution was about *cardinals* – we have not gone beyond the first infinite cardinal.

But that's for another talk.