Recurrent Problems

ITT9132 Concrete Mathematics

Lecture 2 – 4 February 2019

Chapter One

The Tower of Hanoi

Lines in the Plane

The Josephus Problem

Contents

Next section

The Tower of Hanoi: Description

The Tower of Hanoi puzzle was invented by the French mathematician Édouard Lucas in 1883.

- The board has three pegs.
- The tiles are n disks, all of different sizes, with a hole in the middle so that they can be put on the pegs.
- At the beginning of the game, the disks are all on the first peg, in decreasing order from bottom to top (larger at the bottom, smaller at the top)..
- The aim of the game is to put all the disks on the third peg, using the second peg as a help, so that at no time a disk is above a smaller disk.

The Tower of Hanoi: Solution

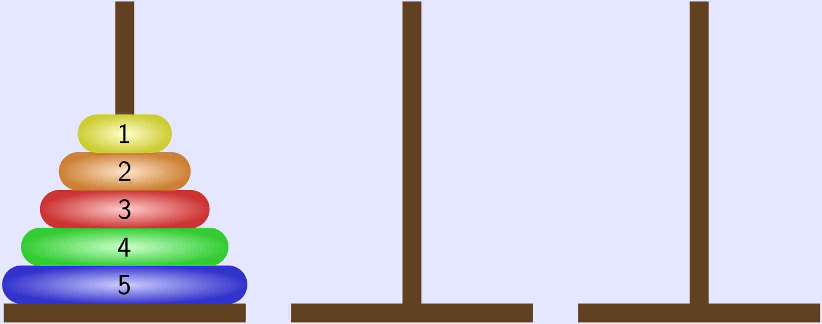
Using mathematical induction the following can be proved:

For the Tower of Hanoi puzzle with $n \geqslant 0$, the minimum number of moves needed is:

$$T_n = 2^n - 1\,.$$

Let's look at the example borrowed from Martin Hofmann and Berteun Damman.

Tower of Hanoi – 5 Discs



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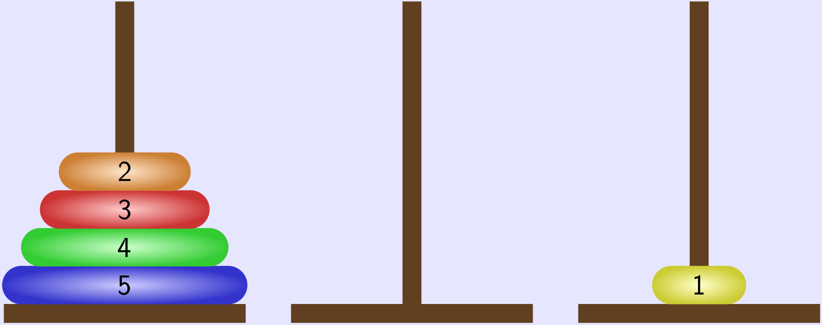
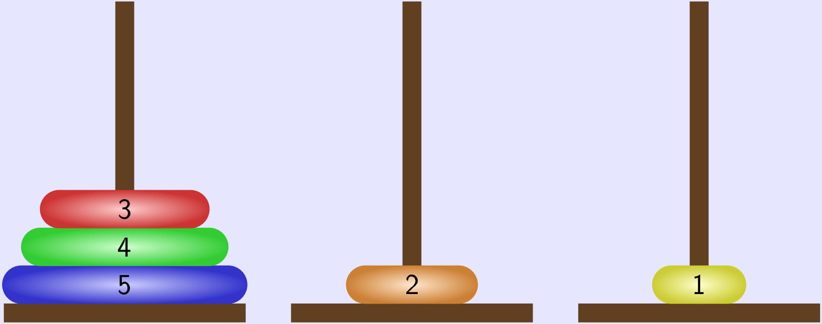


Moved disc from pole 1 to pole 3.

Tower of Hanoi – 5 Discs



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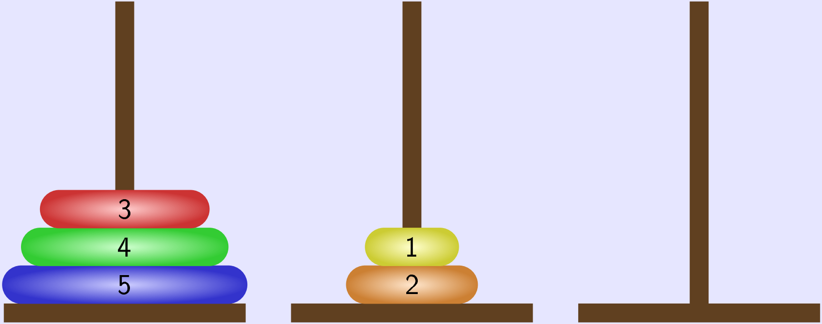

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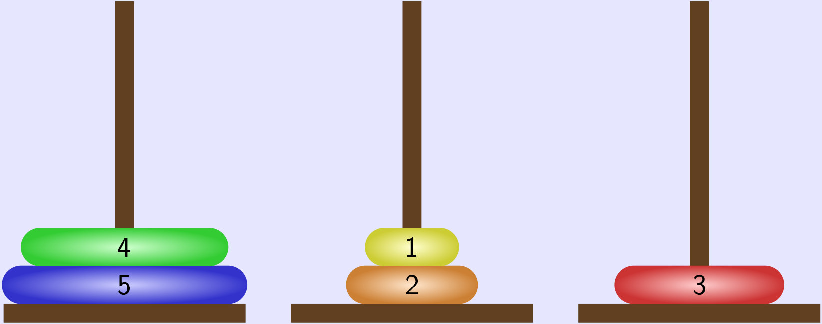

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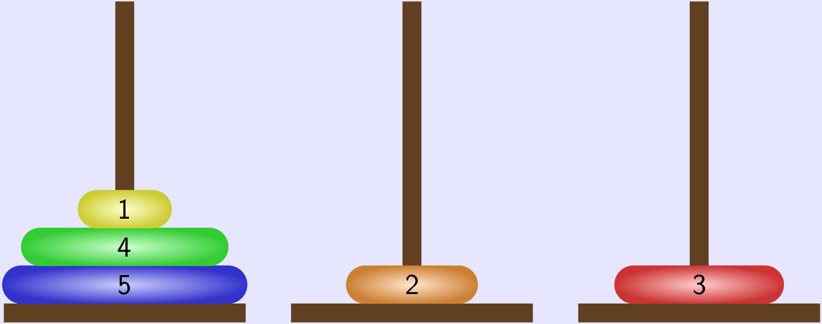

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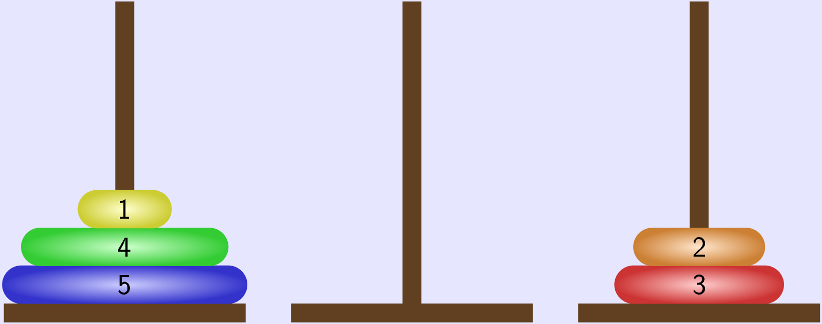

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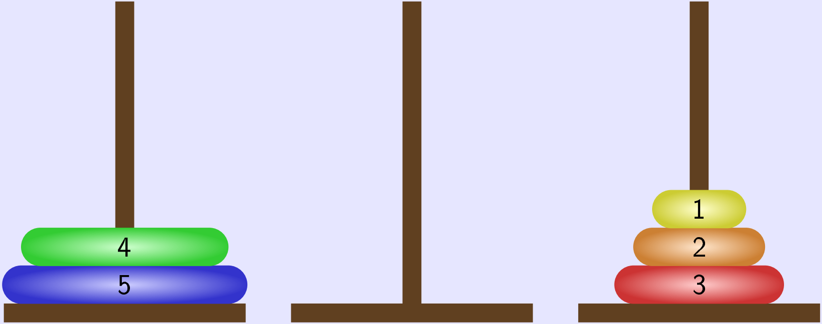

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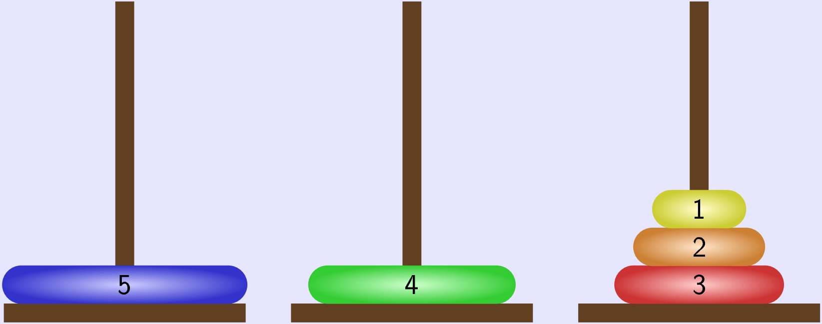

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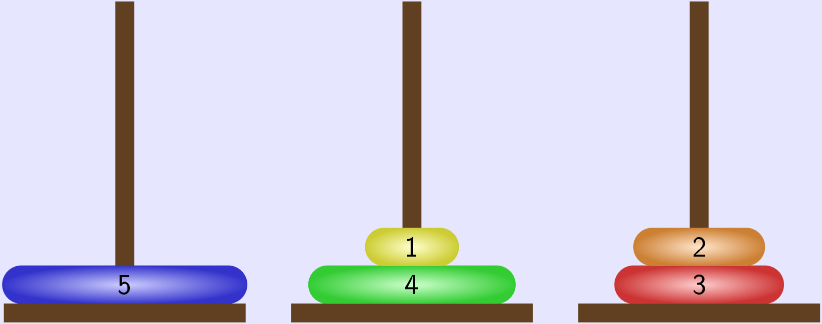

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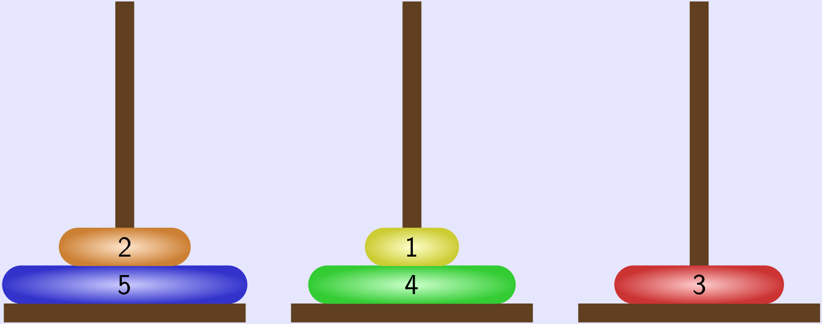

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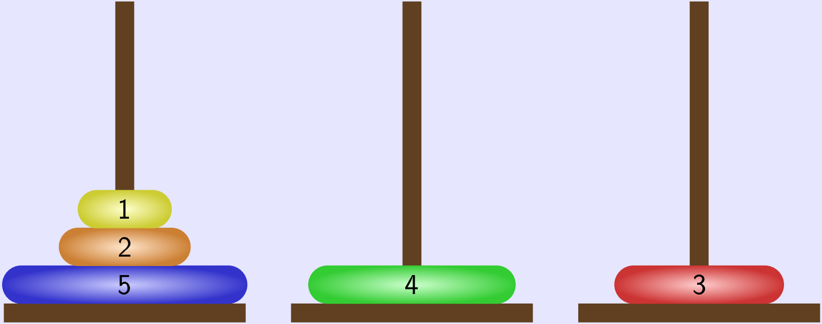

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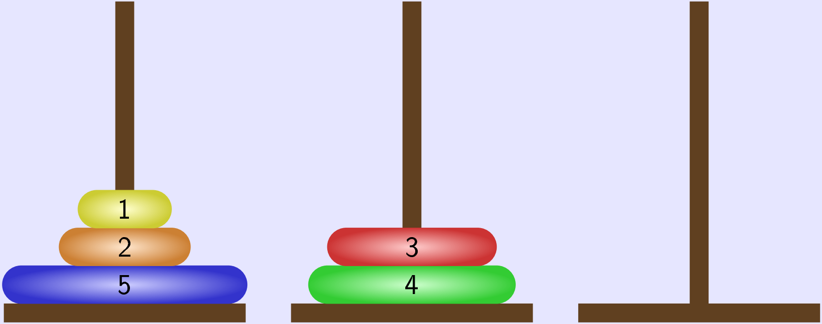

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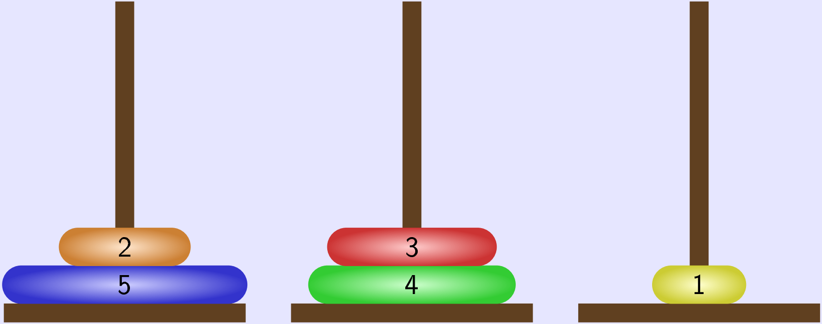

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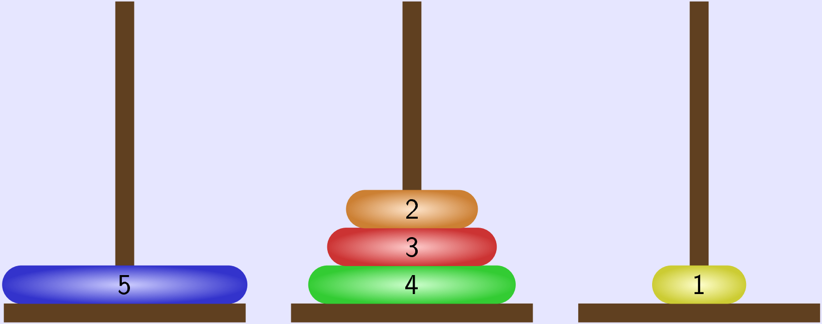

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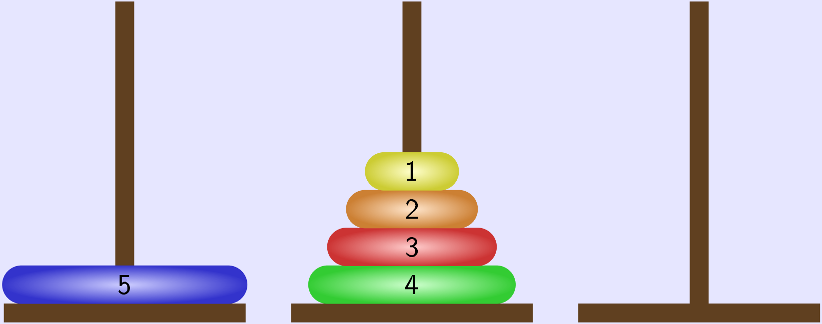

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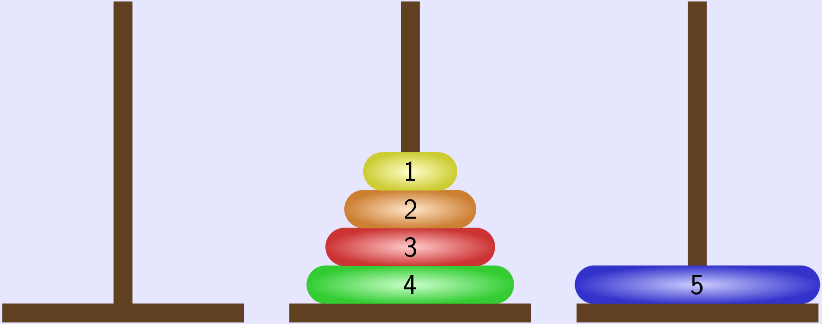

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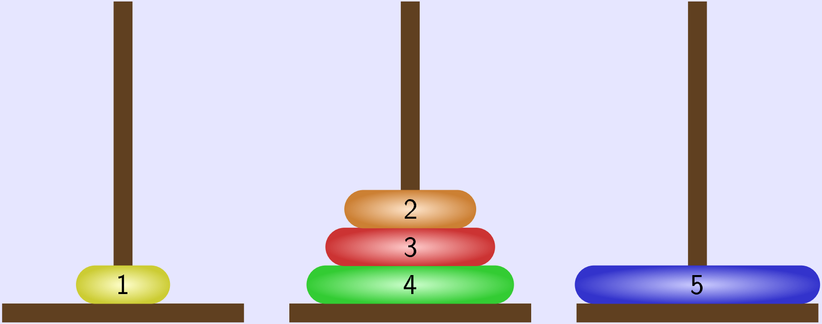

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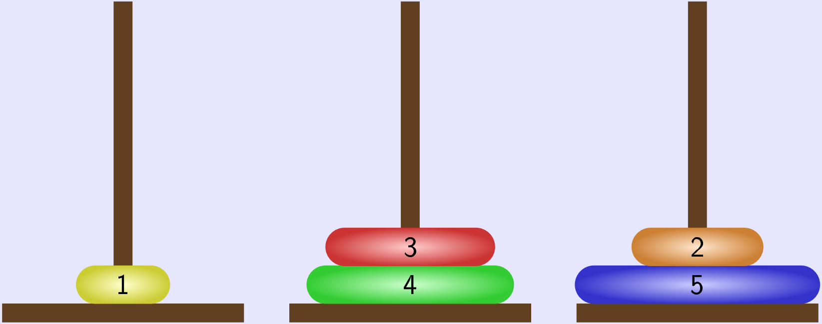

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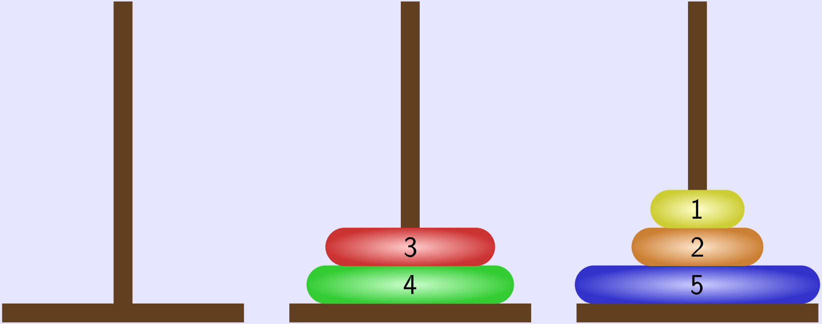

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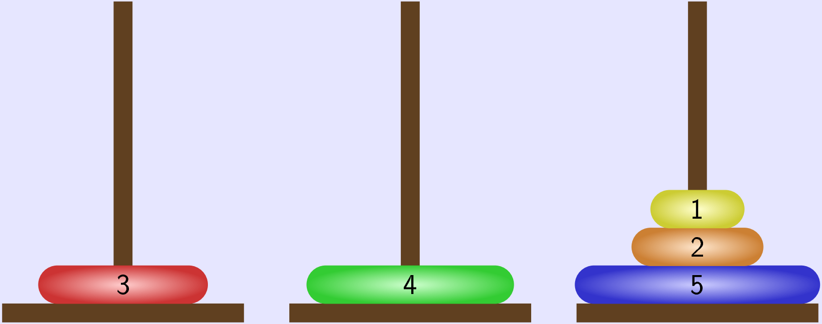

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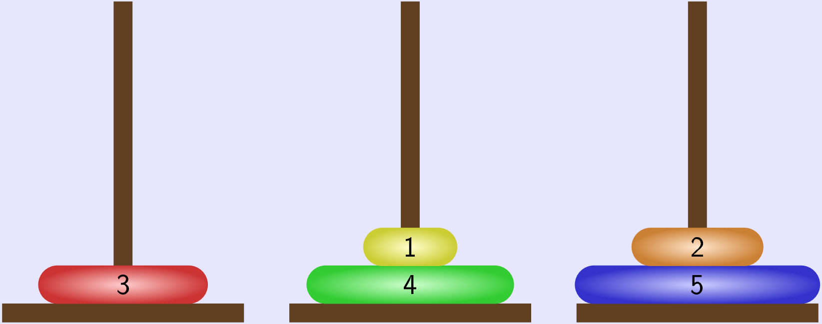

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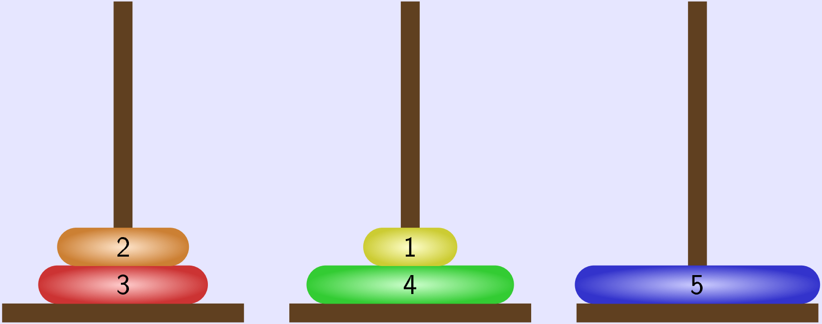

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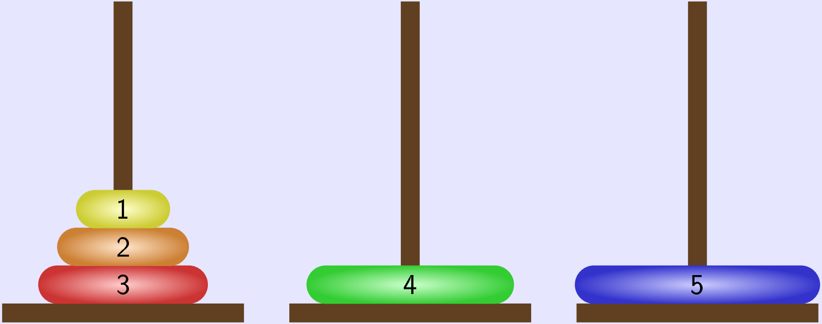

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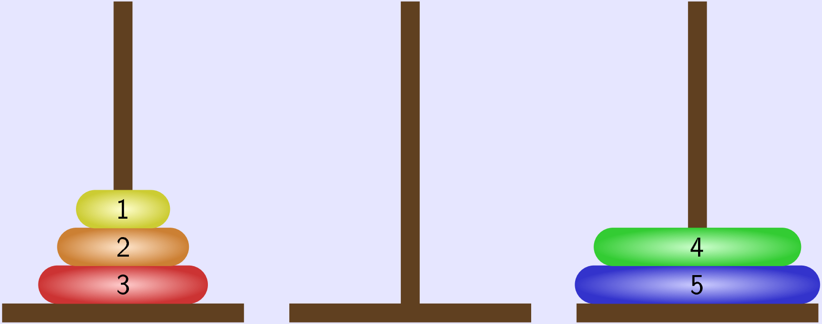

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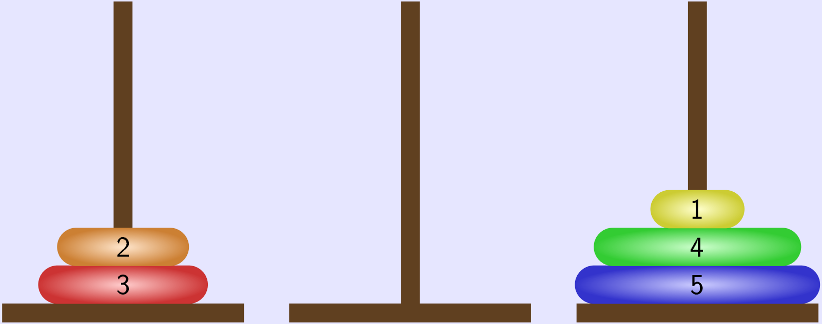

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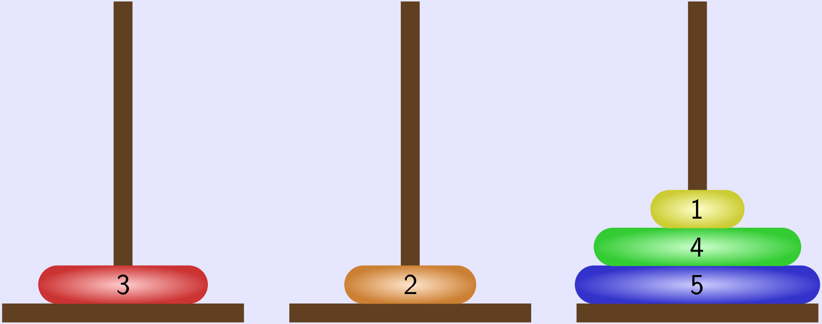

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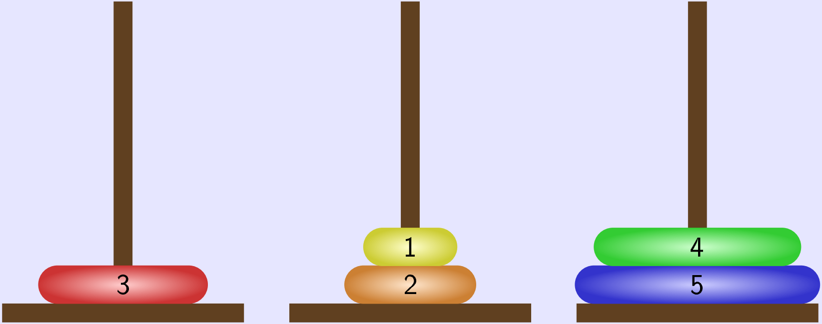
TAL TECH

Tower of Hanoi – 5 Discs



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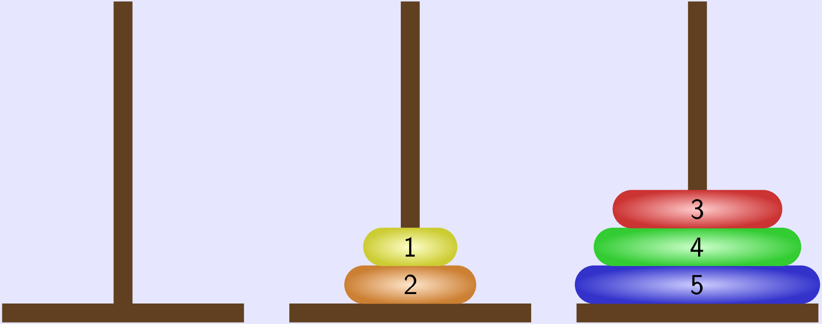

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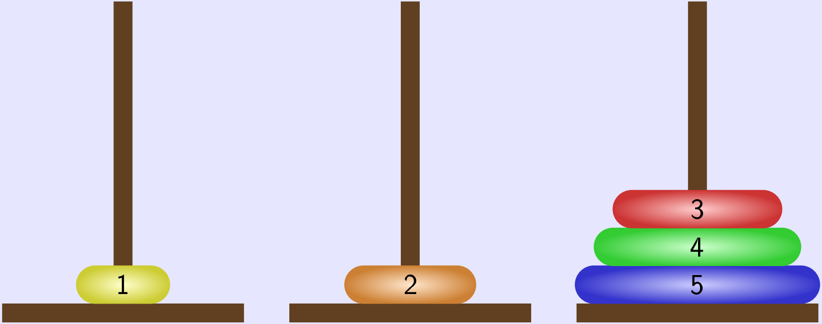

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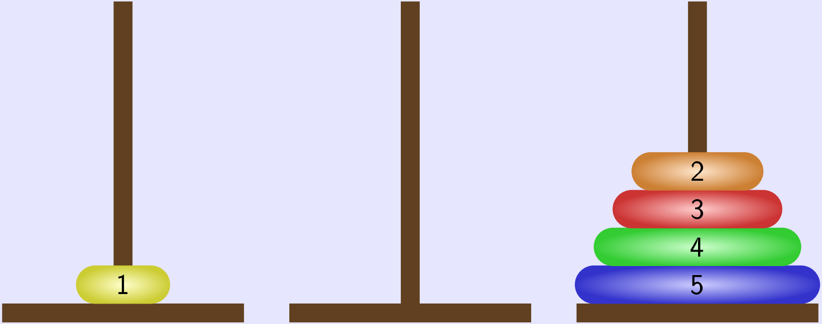

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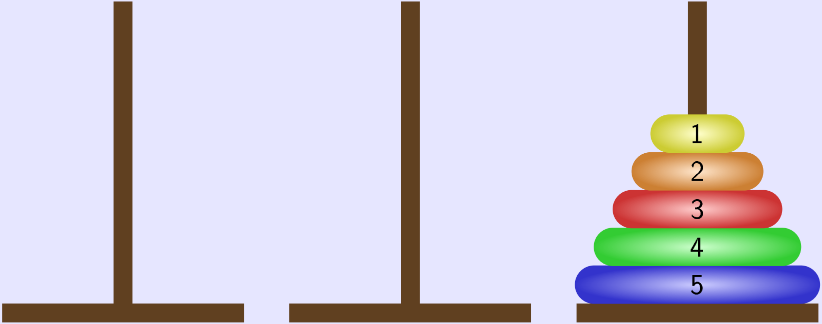

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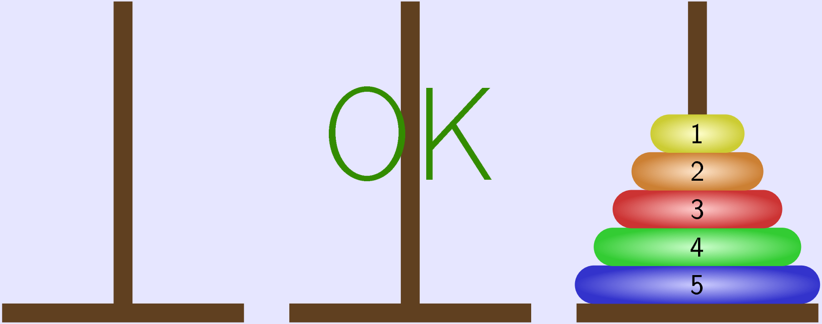

The Principle of Mathematical Induction

Let $P(n)$ be a predicate whose truth or falsehood depends on the value taken by a variable n in the set $\mathbb{N}$ of nonnegative integers. Suppose the following happen:

1. For some $k \in \mathbb{N}$, $P(k)$ is true.
2. For every $n \geqslant k$, the implication $P(n) \longrightarrow P(n+1)$ holds: that is, if $P(n)$ is true, then $P(n+1)$ is also true.

Then $P(n)$ is true for every $n \geqslant k$.

A recursive solution in Python

```python
#!/usr/bin/env python3

import os

def hanoi(n, start='1', step='2', stop='3'):
    '''Solve the Hanoi tower with n disks, from start
    peg to stop peg, using step peg as a spool'''
    if n > 0:
        hanoi(n-1, start, stop, step)
        move(n, start, stop)
        hanoi(n-1, step, start, stop)

def move(n, start, stop):
    '''Display move of disk n from start to stop'''
    print("Disk %d: %s -> %s" % (n, start, stop))

if __name__ == '__main__':
    n = int(input('How many disks? '))
    hanoi(n, '1', '2', '3')
```

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```

Question: why does this program show that $T_n = 2^n - 1$?

Tower of Hanoi: Running time

Base case: $n = 1$.

- Then the Python script only performs `move('1', '3')`, so $T_1 = 1 = 2^1 - 1$.

Inductive step: n disks require 2^{n-1} steps.

- Then the Python script performs:
  - `hanoi(n, '1', '3', '2')`
  - `move('1', '3')`
  - `hanoi(n, '2', '1', '3')`

  which, by inductive hypothesis, requires:

$$T_{n+1} = (2^n - 1) + 1 + (2^n - 1) = 2^{n+1} - 1$$

  moves.

Warmup: What is wrong with this "proof by induction"?

Theorem

All children have the same color of eyes.

"Proof"

The thesis is clearly true for $n = 1$, so let $n > 1$.

1. Put the n children on a line.
2. By inductive hypothesis, the $n-1$ *leftmost* children have the same color of eyes, and so do the $n-1$ *rightmost* children.
3. Then the $n-2$ children *in the middle* have the same color of eyes.
4. The first and last child must then have *that* color of eyes.

Warmup: What is wrong with this "proof by induction"?

Theorem

All children have the same color of eyes.

Solution

The problem is with:

- Then the $n-2$ children *in the middle* have the same color of eyes.

For $n=2$ there are no "$n-2$ children in the middle".
So the implication $P(n) \longrightarrow P(n+1)$ is not true for every $n \geq 1$.

Next section

Lines in the Plane

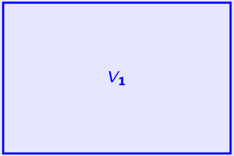
Problem

Popularly: How many slices of pizza can a person obtain by making n straight cuts with a pizza knife?

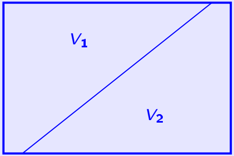
Academically: What is the maximum number L_n of regions defined by n lines in the plane?

Solved first in 1826, by the Swiss mathematician Jacob Steiner .

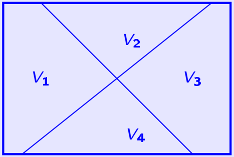
Lines in the Plane – small cases



$L_0 = 1$



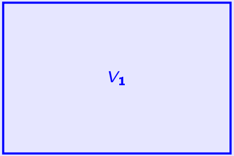
$L_1 = 2$



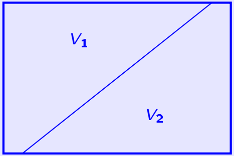
$L_2 = 4$

$L_3 = L_2 + 3 = 7$

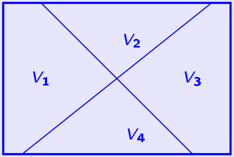
Lines in the Plane – small cases



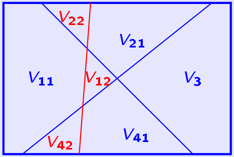
$$L_0 = 1$$



$$L_1 = 2$$



$$L_2 = 4$$



$$L_3 = L_2 + 3 = 7$$

Lines in the Plane – generalization

Observation:

The n-th line (for $n > 0$) increases the number of regions by k

iff it splits k of the "old regions"

iff it hits the previous lines in $k - 1$ different places.

Lines in the Plane – generalization

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Then k must be less or equal to n. – Why?

Lines in the Plane – generalization

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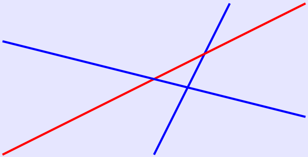
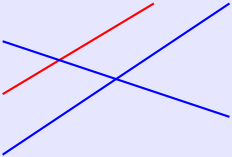


$k = 3$; 2 places



$k = 2$; 1 places

Lines in the Plane – generalization (2)

Therefore the new line can intersect the $n-1$ "old" lines in at most "$n-1$" different points, we have established the upper bound:

$$\boxed{L_n \leqslant L_{n-1} + n \qquad \text{for } n > 0.}$$

If n-th line is not parallel to any of the others (hence it intersects them all), and doesn't go through any of the existing intersection points (hence it intersects them all in different places) then we get the recurrence equation:

$$\begin{aligned} L_0 &= 1; \\ L_n &= L_{n-1} + n \qquad \text{for } n > 0. \end{aligned}$$

n	0	1	2	3	4	5	6	7	8	9	$\cdots$
L_n	1	2	4	7	11	16	22	29	37	46	$\cdots$

Lines in the Plane – solving recurrence

Observation:

$$
\begin{aligned}
L_n &= L_{n-1} + n \\
&= L_{n-2} + (n-1) + n \\
&= L_{n-3} + (n-2) + (n-1) + n \\
&= \cdots \\
&= L_0 + 1 + 2 + \ldots + (n-2) + (n-1) + n \\
&= 1 + S_n\,,
\end{aligned}
$$

where $S_n = 1 + 2 + 3 + \ldots + (n-1) + n$.

Lines in the Plane – solving recurrence (2)

Evaluation of $S_n = 1 + 2 + \cdots + (n-1) + n$.

Recurrent equation:

$$\begin{aligned} S_0 &= 0\,; \\ S_n &= S_{n-1} + n \ \forall n \geq 1\,. \end{aligned}$$

Solution (Gauss, 1786):

$$\begin{array}{ccccccccccc} S_n & = & 1 & + & 2 & + & \ldots & + & (n-1) & + & n \\ +S_n & = & n & + & (n-1) & + & \ldots & + & 2 & + & 1 \\ \hline 2S_n & = & (n+1) & + & (n+1) & + & \ldots & + & (n+1) & + & (n+1) \end{array}$$

Then $2S_n = n \cdot (n-1)$, so that $S_n = \dfrac{n(n+1)}{2}$.

Lines in the Plane – solving recurrence (2)

Evaluation of $S_n = 1 + 2 + \cdots + (n-1) + n$.

Recurrent equation:

$$\begin{array}{rcl} S_0 & = & 0\,; \\ S_n & = & S_{n-1} + n \ \forall n \geq 1\,. \end{array}$$

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Then $2S_n = n \cdot (n-1)$, so that $S_n = \dfrac{n(n+1)}{2}$.

Lines in the Plane – solving recurrence (3)

Theorem: Closed formula for L_n

$$L_n = \frac{n(n+1)}{2} + 1 \text{ for} n > 0 .$$

Proof (by induction).

Basis: $L_0 = \frac{0(0+1)}{2} + 1 = 1$.

Step: Let assume $L_n = \frac{n(n+1)}{2} + 1$ and evaluate

$$\begin{aligned}
L_{n+1} &= L_n + n + 1 \\
&= \frac{n(n+1)}{2} + 1 + n + 1 \\
&= \frac{n(n+1) + 2 + 2n}{2} + 1 \\
&= \frac{n(n+1) + 2(n+1)}{2} + 1 \\
&= \frac{(n+1)(n+2)}{2} + 1 .
\end{aligned}$$

Q.E.D.

Next section

The Josephus Problem

Legend:

During the Jewish-Roman war, Flavius Josephus, a famous historian of the first century, was among a band of 41 Jewish rebels trapped in a cave by the Romans. Preferring suicide to capture, the rebels decided to form a circle and, proceeding around it, to kill every third remaining person until no one was left. But Josephus, together with his friend, wanted to avoid being killed. So he quickly calculated where he and his friend should stand in the vicious circle

The Josephus Problem

Our variation of the problem:

- We start with n people numbered 1 to n around a circle.
- We eliminate every second remaining person until only one survives.

Task is to compute the survivor's number, $J(n)$

Example, $n = 10$.

The elimination order is 2, 4, 6, 8, 10, 3, 7, 1, 9. So, we have $J(10) = 5$

The Josephus Problem

Our variation of the problem:

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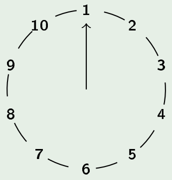

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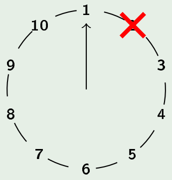

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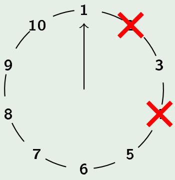

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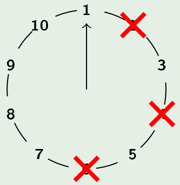

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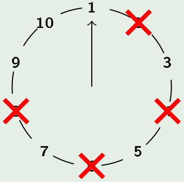

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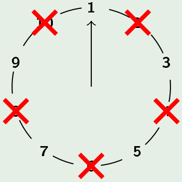

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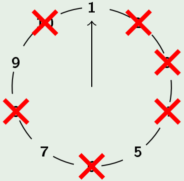

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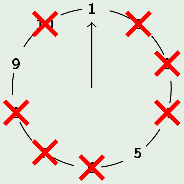

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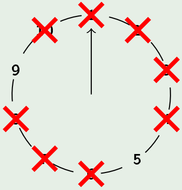

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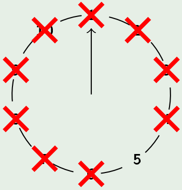

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The Josephus Problem – small numbers

Evaluate $J(n)$ for small n:

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	$\cdots$
$J(n)$	1	1	3	1	3	5	7	1	3	5	7	9	11	13	15	1	$\cdots$

Properties

1. $J(n)$ is always odd;
2. Recurrence equation:

$$\begin{aligned} J(1) &= 1\,; \\ J(2n) &= 2J(n)-1 \text{ for } n \geqslant 1\,; \\ J(2n+1) &= 2J(n)+1 \text{ for } n \geqslant 1\,. \end{aligned}$$

3. Closed formula:

$$J(2^m+\ell) = 2\ell+1 \quad \text{for } m \geqslant 0 \text{ and } 0 \leqslant \ell < 2^m\,.$$

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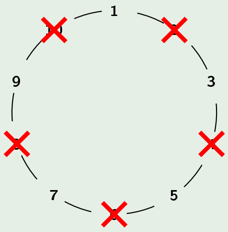
The Josephus Problem – recurrent equation (1)

Case $n = 2m$.



First trip eliminates all even numbers. Then we change numbers and repeat:

Old number k	1	3	5	7	9
New number k'	1	2	3	4	5

or

$$k = 2k' - 1\,.$$

That correspondance between "old" and "new number" gives us that:
$J(2n) = 2J(n) - 1$

The Josephus Problem – recurrent equation (1)

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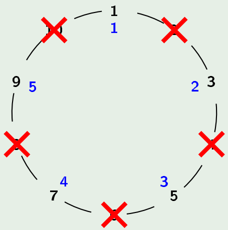

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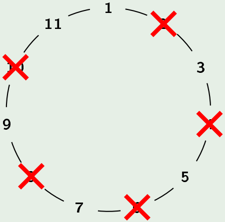
The Josephus Problem – recurrent equation (2)

Case $n = 2m + 1$.



First trip eliminates all even numbers. Then we change numbers and repeat:

Old number k	1	3	5	7	9	11
New number k'	0	1	2	3	4	5

or

$$k = 2k' + 1$$

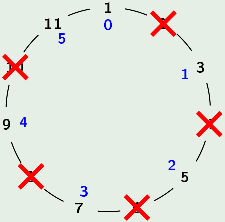
That correspondence between “old” and “new” numbers givs us that:

$J(2n+1) = 2J(n) + 1$

.

The Josephus Problem – recurrent equation (2)

Case $n = 2m+1$.



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That correspondence between "old" and "new" numbers givs us that:

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.

The Josephus Problem – application of recurrence

The equation

$$\begin{aligned} J(1) &= 1\,; \\ J(2n) &= 2J(n)-1 \text{ for } n \geqslant 1\,; \\ J(2n+1) &= 2J(n)+1 \text{ for } n \geqslant 1 \end{aligned}$$

can be used for computing function for large arguments.

For example

$$\begin{aligned} J(86) &= 2J(43)-1 &= 45 \\ J(43) &= 2J(21)+1 &= 23 \\ J(21) &= 2J(10)+1 &= 11 \\ J(10) &= 5 \end{aligned}$$

The Josephus Problem – closed formula

Theorem

$$J(2^m + \ell) = 2\ell + 1 \text{ for } m \geqslant 0 \text{ and } 0 \leqslant \ell < 2^m \,.$$

Proof by induction over m.

Basis If $m = 0$ then also $\ell = 0$, and $J(1) = 1$.

Step

- If $m > 0$ and $2^m + \ell = 2n$, then ℓ is even and:

  $$J(2^m + \ell) = 2J(2^{m-1} + \ell/2) - 1 = 2(2\ell/2 + 1) - 1 = 2\ell + 1 \,.$$

- If $2^m + \ell = 2n + 1$, then:

  $$J(2n+1) = 2 + J(2n) = 2 + 2(\ell - 1) + 1 = 2\ell + 1$$

Q.E.D.

The Josephus Problem – closed formula (2)

Closed formula can be used for computing function $J(n)$:

Example

We have $1030 = 2^{10} + 6$, so $J(1030) = 2 \cdot 6 + 1 = 13$.

Next section

Structural induction

Premises

Let S be a set having the following features:

1. A set S_B of basic cases is contained in S.
2. Finitely many operations $u_i : S^{m_i} \to S$, $i = 1, \ldots, n$, exist such that, if $x_1, \ldots, x_{m_i} \in S$, then $u_i(x_1, \ldots, x_{m_i}) \in S$.
3. Nothing else belongs to S.

Technique

Let P be a property such that:

1. Each base case $x \in S_B$ has property P.
2. For every $i = 1, \ldots, n$ and every $x_1, \ldots, x_{m_i} \in S$, if each value $x_1, \ldots, x_{m_i}$ has property P, then $u_i(x_1, \ldots, x_{m_i})$ has property P.

Then every element of S has property P.

Mathematical induction as structural induction

Premises

The set $S = \mathbb{N}$ of natural numbers is constructed as follows:

1. A set $S_B = \{0\}$ of basic cases is contained in $\mathbb{N}$.
2. A single operation, the *successor*, $s : \mathbb{N} \to \mathbb{N}$, exists such that, if $n \in \mathbb{N}$, then $s(n) \in \mathbb{N}$.
3. Nothing else belongs to $\mathbb{N}$.

Technique

Let P be a property such that

1. 0 has property P.
2. For every $n \in \mathbb{N}$, if n has property P, then $s(n)$ has property P.

Then every $n \in \mathbb{N}$ has property P.

Structural induction on positive integers

The set $S = \mathbb{Z}^+$ of positive integers is constructed as follows:

1. A set $S_B = \{1\}$ of basic cases is contained in $\mathbb{Z}^+$.
2. Two operations:
   1. doubling $d : \mathbb{Z}^+ \to \mathbb{Z}^+, d(n) = 2n$;
   2. doubling increased $sd : \mathbb{Z}^+ \to \mathbb{Z}^+, sd(n) = 2n + 1$;

   exists such that, if $n \in \mathbb{Z}^+$, then $d(n), sd(n) \in \mathbb{Z}^+$.
3. Nothing else belongs to $\mathbb{Z}^+$.

Let P be a property such that

1. 1 has property P.
2. For every $n \in \mathbb{Z}^+$, if n has property P, then $d(n)$ and $sd(n)$ have property P.

Then every $n \in \mathbb{Z}^+$ has property P.

Next section

Binary expansion of $n = 2^m + \ell$

Denote

$$n = (b_m b_{m-1} \dots b_1 b_0)_2$$

where $b_i \in \{0, 1\}$ and $b_m = 1$.

This notation stands for

$$n = b_m 2^m + b_{m-1} 2^{m-1} + \dots + b_1 2 + b_0$$

For example

$$20 = (10100)_2 \quad \text{and} \quad 83 = (1010011)_2$$

Binary expansion of $n = 2^m + \ell$, where $0 \leqslant \ell < 2^m$

Observations:

1. $\ell = (0b_{m-1} \dots b_1 b_0)_2$.
2. $2\ell = (b_{m-1} \dots b_1 b_0 0)_2$.
3. $2^m = (10 \dots 00)_2$ and $1 = (00 \dots 01)_2$.
4. $n = 2^m + \ell = (1b_{m-1} \dots b_1 b_0)_2$.
5. $2\ell + 1 = (b_{m-1} \dots b_1 b_0 1)_2$

Corollary

$$J((\boxed{1}\ b_{m-1} \dots b_1 b_0)_2 = (b_{m-1} \dots b_1 b_0\ \boxed{1})_2$$

shift

Binary expansion of $n = 2^m + \ell$, where $0 \leqslant \ell < 2^m$

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1. $\ell = (0 b_{m-1} \dots b_1 b_0)_2$.
2. $2\ell = (b_{m-1} \dots b_1 b_0 0)_2$.
3. $2^m = (10\dots00)_2$ and $1 = (00\dots01)_2$.
4. $n = 2^m + \ell = (1 b_{m-1} \dots b_1 b_0)_2$.
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shift

Binary expansion of $n = 2^m + \ell$, where $0 \leqslant \ell < 2^m$

Example

$$
\begin{aligned}
100 &= 64 + 32 + 4 \\
J(100) &= J((1100100)_2) = (1001001)_2 \\
J(100) &= 64 + 8 + 1 = 73
\end{aligned}
$$