

# Recursion



# Plan

Recursion is one of the most important techniques in computer science.

The main idea is to capture the invariants over repeated actions.

- Setting up recurrences
  - Fibonacci recurrence
  - Problem solving recurrences
  - Catalan recurrences
- Solving recurrences

# Recursively Defined Sequences

We can define a sequence by specifying relation between the current term and the previous terms.

- Arithmetic sequence:  $(a, a+d, a+2d, a+3d, \dots, )$

recursive definition:  $a_0=a, a_{i+1}=a_i+d$

- Geometric sequence:  $(a, ra, r^2a, r^3a, \dots, )$

recursive definition:  $a_0=a, a_{i+1}=ra_i$

- Harmonic sequence:  $(1, 1/2, 1/3, 1/4, \dots, )$

recursive definition:  $a_0=1, a_{i+1}=ia_i/(i+1)$

# Rabbit Populations

## The Rabbit Population



- A mature boy/girl rabbit pair reproduces every month.
- Rabbits mature after one month.

$w_n ::= \# \text{ newborn pairs in the } n\text{-th month}$

$r_n ::= \# \text{ pairs in the } n\text{-th month}$

- Start with a newborn pair:  $w_0 = 1, r_0 = 0$

How many rabbits after  $n$  months?

# Rabbit Populations

$w_n ::= \# \text{ newborn pairs in the } n\text{-th month}$

$r_n ::= \# \text{ pairs in the } n\text{-th month}$

$$r_1 = 1$$

$$r_n = r_{n-1} + w_{n-1}$$

$$w_n = r_{n-1} \text{ so}$$

$$r_n = r_{n-1} + r_{n-2}$$



Rabbits could overpopulate easily, see [Rabbits in Australia](#) for example.

It was [Fibonacci](#) who studied rabbit population growth.

We will compute the closed form for  $r_n$  soon.

A formula so that  $\#$  steps for calculating  $r_n \leq \text{constant}$

# Warm Up

We will solve counting problems by setting up recurrence relations.

First we use recursion to count something we already know, to get familiar with this approach.

Let us count the number of elements in  $\text{pow}(S_n)$  where  $S_n = \{a_1, a_2, \dots, a_n\}$  is an  $n$ -element set.

Let  $r_n$  be the size of  $\text{pow}(S_n)$ .

Then  $r_1 = 2$ , where  $\text{pow}(S_1) = \{\Phi, \{a_1\}\}$

$r_2 = 4$ , where  $\text{pow}(S_2) = \{\Phi, \{a_1\}, \{a_2\}, \{a_1, a_2\}\}$

## Warm Up

Let  $r_n$  be the size of  $\text{pow}(S_n)$  where  $S_n = \{a_1, a_2, \dots, a_n\}$  is an  $n$ -element set.

Then  $r_1 = 2$ , where  $\text{pow}(S_1) = \{\Phi, \{a_1\}\}$

$r_2 = 4$ , where  $\text{pow}(S_2) = \{\Phi, \{a_1\}, \{a_2\}, \{a_1, a_2\}\}$

The main idea of recursion is to define  $r_n$  in terms of the previous  $r_i$ .

How to define  $r_3$  in terms of  $r_1$  and  $r_2$ ?

$\text{pow}(S_3) =$  the union of  $\{\Phi, \{a_1\}, \{a_2\}, \{a_1, a_2\}\}$



and  $\{a_3, \{a_1, a_3\}, \{a_2, a_3\}, \{a_1, a_2, a_3\}\}$

So  $r_3 = 2r_2$ .


while the lower sets are obtained by adding  $a_3$  to the upper sets.

## Warm Up

Let  $r_n$  be the size of  $\text{pow}(S_n)$  where  $S_n = \{a_1, a_2, \dots, a_n\}$  is an  $n$ -element set.

The main idea of recursion is to define  $r_n$  in terms of the previous  $r_i$ .

$\text{pow}(S_n) = \text{the union of } S_{n-1} = \{\Phi, \{a_1\}, \{a_2\}, \dots, \{a_1, a_2, \dots, a_{n-1}\}\}$

  
and  $\{a_n, \{a_1, a_n\}, \{a_2, a_n\}, \dots, \{a_1, a_2, \dots, a_{n-1}, a_n\}\}$

while the lower sets are obtained by adding  $a_n$  to the upper sets.

Every subset is counted exactly once.

$$\text{So } r_n = 2r_{n-1}.$$

Solving this recurrence relation will show that  $r_n = 2^n$  (geometric sequence).



# Number of Bit Strings without a Specific Pattern

How many  $n$ -bit strings without the bit pattern 11?

Let  $r_n$  be the number of such strings.

$$\text{e.g. } r_1 = |\{0, 1\}| = 2,$$

$$r_2 = |\{00, 01, 10\}| = 3$$

$$r_3 = |\{000, 001, 010, 100, 101\}| = 5$$

$$r_4 = |\{0000, 0001, 0010, 0100, 0101, 1000, 1001, 1010\}| = 8$$

Can you see the pattern?

$$\begin{aligned} r_4 &= |\{\textcolor{red}{0}000, \textcolor{red}{0}001, \textcolor{red}{0}010, \textcolor{red}{0}100, \textcolor{red}{0}101\} \text{ union} \\ &\quad \{\textcolor{red}{1}000, \textcolor{red}{1}001, \textcolor{red}{1}010\}| \\ &= 5 + 3 = 8 \end{aligned}$$

# Number of Bit Strings without a Specific Pattern

How many  $n$ -bit strings without the bit pattern 11?

Let  $r_n$  be the number of such strings.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?

Case 1: The first bit is 0.

Then any  $(n-1)$ -bit string without the bit pattern 11  
can be appended to the end to form an  $n$ -bit string without 11.  
So in this case there are exactly  $r_{n-1}$  such  $n$ -bit strings.

0 +

00000000000000000000  
00000000000000000001  
...  
10101010101010101010

The set of all  $(n-1)$ -bit  
strings without 11.

Totally  $r_{n-1}$  of them.

# Number of Bit Strings without a Specific Pattern

How many  $n$ -bit strings without the bit pattern 11?

Let  $r_n$  be the number of such strings.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?

Case 2: The first bit is 1.

Then the second bit must be 0, because we can't have 11.

Then any  $(n-2)$ -bit string without the bit pattern 11

can be appended to the end to form an  $n$ -bit string without 11.

So in this case there are exactly  $r_{n-2}$  such  $n$ -bit strings.

10 +

000000000000000000  
000000000000000001  
...  
101010101010101010

The set of all  $(n-2)$ -bit strings without 11.

Totally  $r_{n-2}$  of them.

# Number of Bit Strings without a Specific Pattern

How many  $n$ -bit string without the bit pattern 11?

0 +

000000000000000000  
000000000000000001  
...  
1010101010101010101

The set of all  $(n-1)$ -bit strings without 11.  
Totally  $r_{n-1}$  of them.

10 +

000000000000000000  
000000000000000001  
...  
101010101010101010

The set of all  $(n-2)$ -bit strings without 11.  
Totally  $r_{n-2}$  of them.

Every string without the bit pattern 11 is counted exactly once.

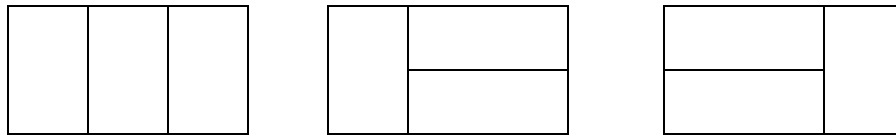
Therefore,  $r_n = r_{n-1} + r_{n-2}$

## Exercise

How many  $n$ -bit strings without the bit pattern 111?

# Domino

Given a  $2 \times n$  puzzle, how many ways to fill it with dominos ( $2 \times 1$  tiles)?



E.g. There are 3 ways to fill a  $2 \times 3$  puzzle with dominos.

Let  $r_n$  be the number of ways to fill a  $2 \times n$  puzzle with dominos.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?

# Domino

Given a  $2 \times n$  puzzle, how many ways to fill it with dominos ( $2 \times 1$  tiles)?

Let  $r_n$  be the number of ways to fill a  $2 \times n$  puzzle with dominos.

Case 1: put the domino vertically



Case 2: put the domino horizontally



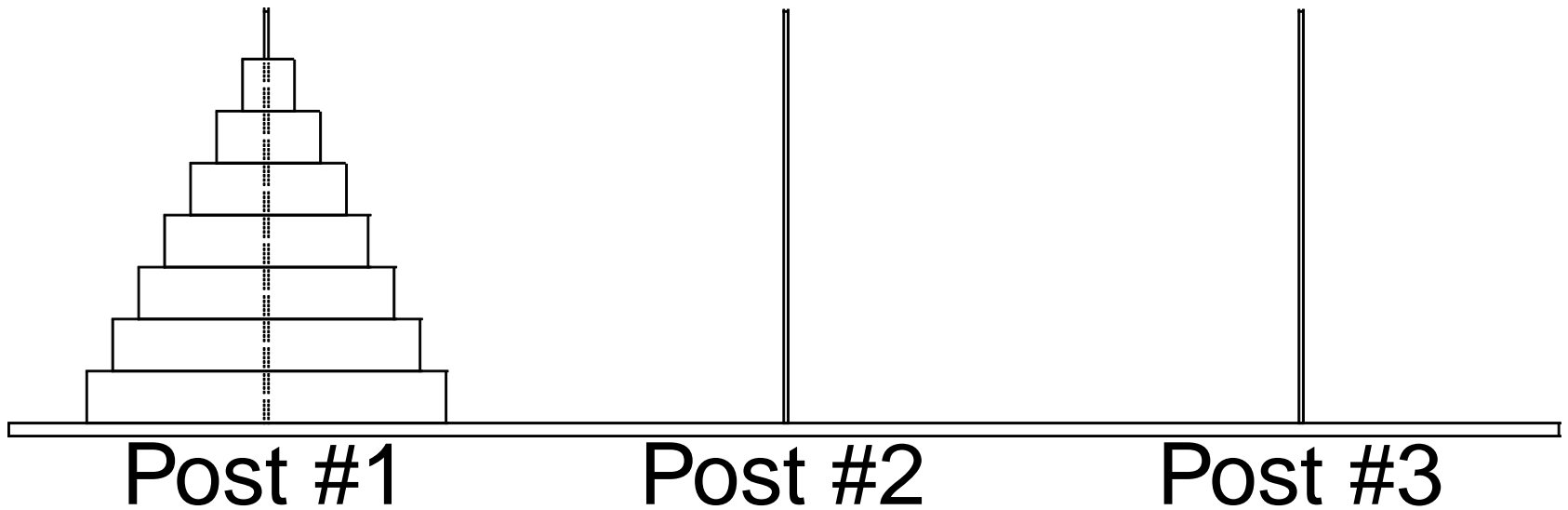
Therefore,  $r_n = r_{n-1} + r_{n-2}$

# Plan

- Setting up recurrences
  - Fibonacci recurrence
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# Tower of Hanoi

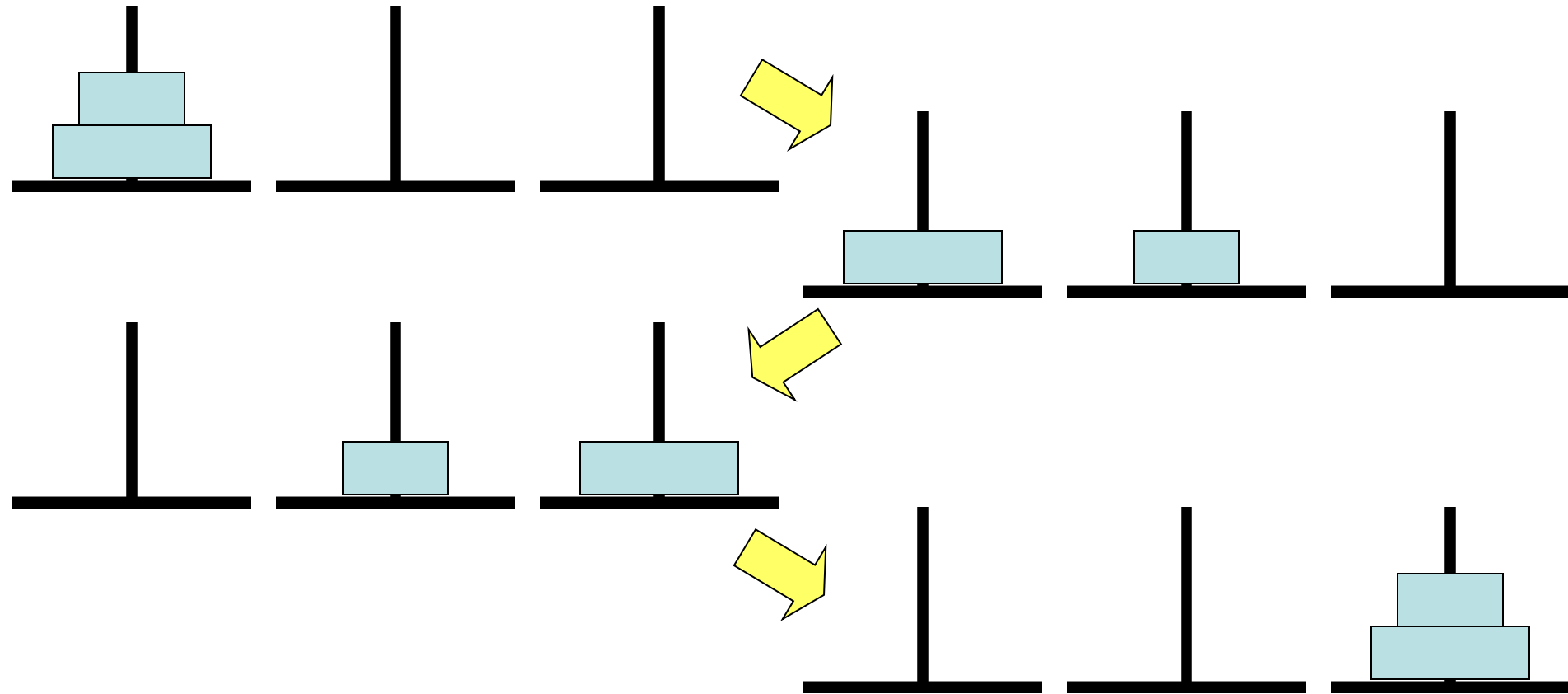


The goal is to move all the disks to post 3.

The rule is that a bigger disk cannot be placed on top of a smaller disk.

# Tower of Hanoi

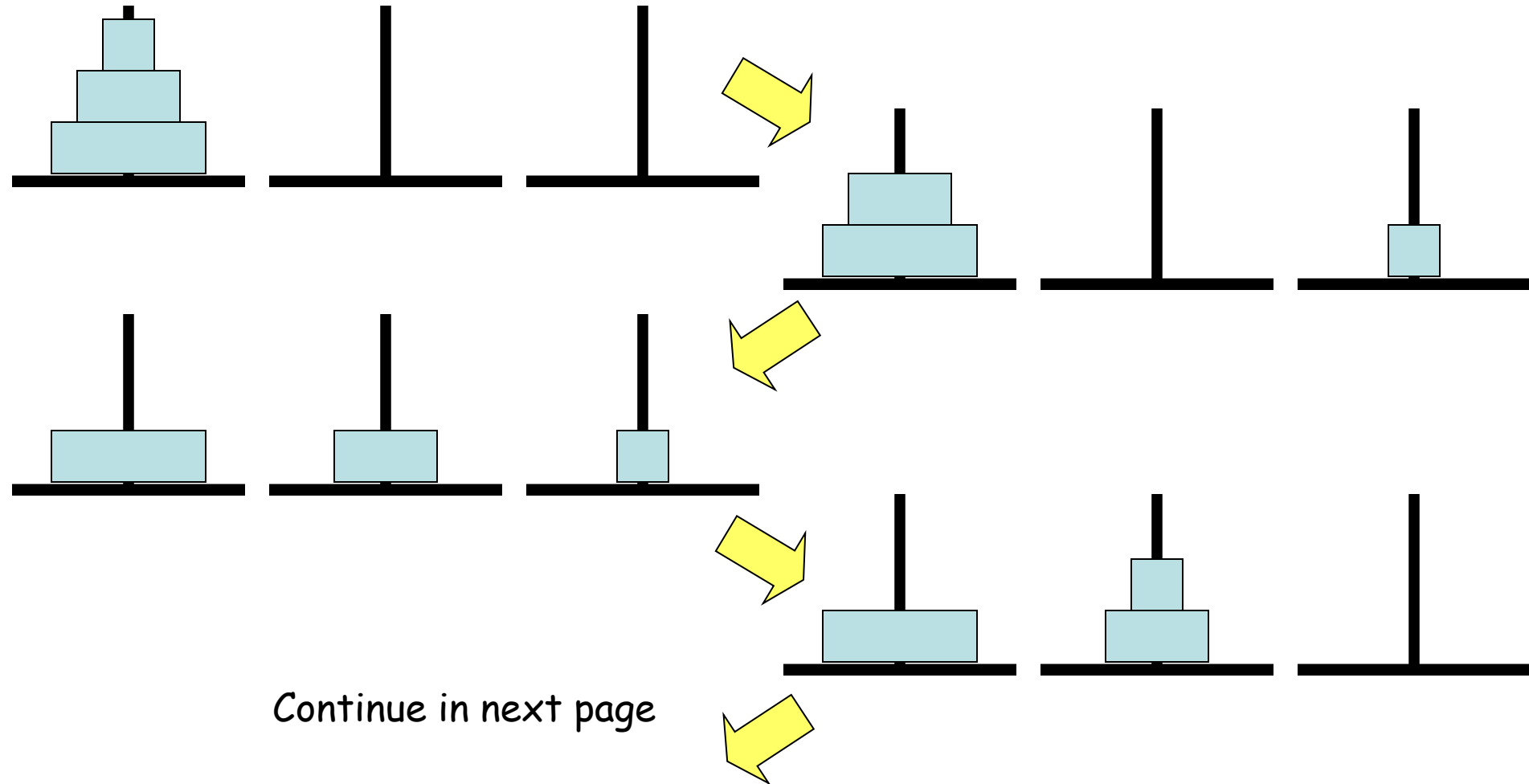
It is easy if we only have 2 disks.



A total of 3 steps.

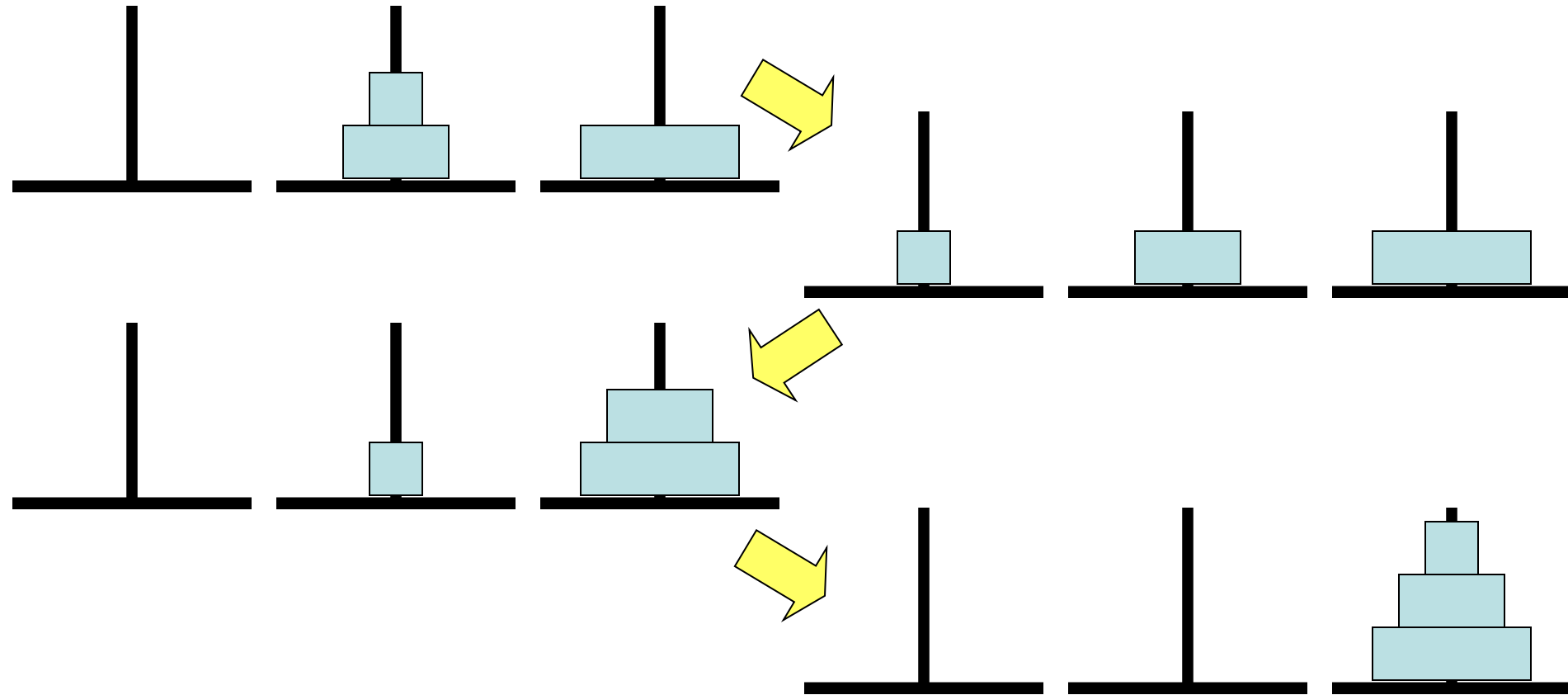
# Tower of Hanoi

It is not difficult if we only have 3 disks.



# Tower of Hanoi

It is not difficult if we only have 3 disks.



A total of seven steps.

# Tower of Hanoi

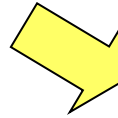
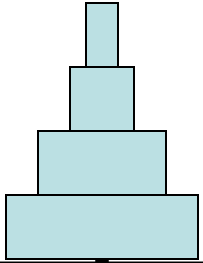


Can you write a program to solve this problem?

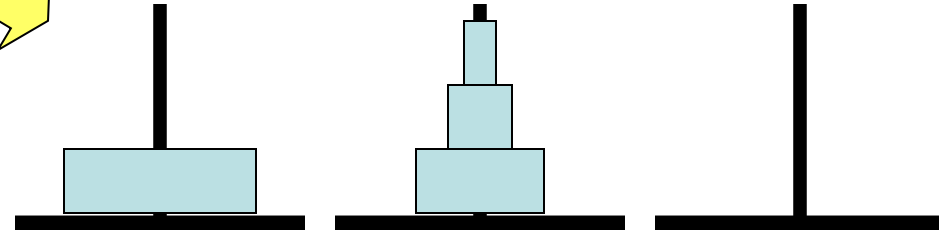
Think recursively!

# Tower of Hanoi

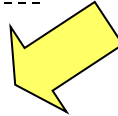
Suppose you already have a program for 3 disks.  
Can you use it to solve 4 disks?



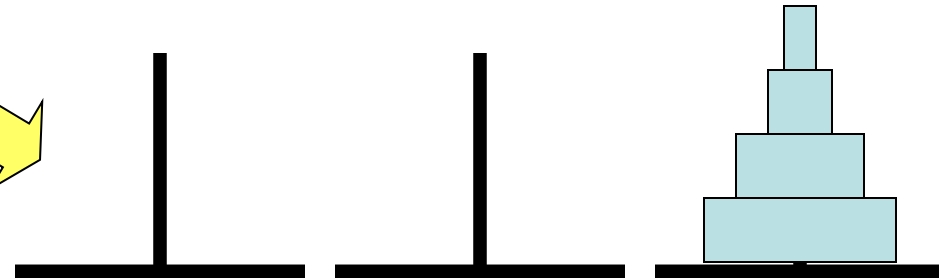
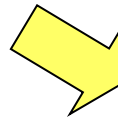
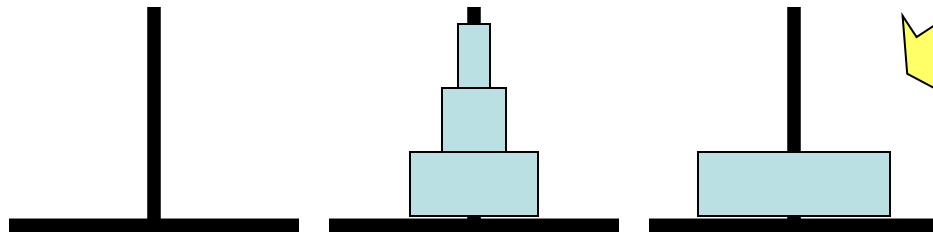
In order to move the largest disk, I have to move the top 3 disks first, so I can use the program for 3 disks.



Then I move the largest disk.



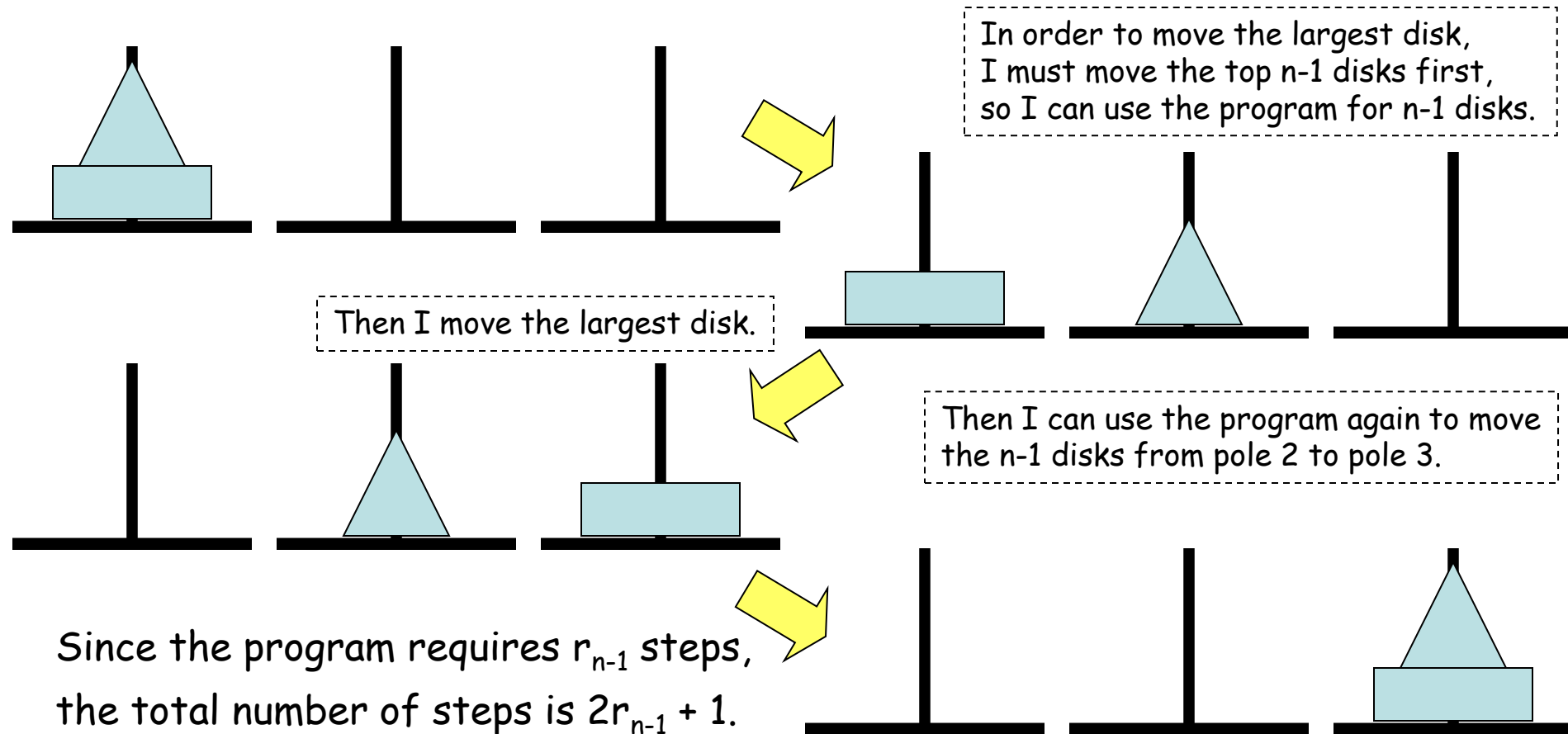
Then I can use the program to move the 3 disks from pole 2 to pole 3.



Since the program requires 7 steps,  
the total number of steps is 15.

# Tower of Hanoi

This recursion is true for any  $n$ .



$$r_n = 2r_{n-1} + 1$$

# Optimality

What will be the minimum number of steps needed if we have 4 poles?

Frame-Stewart algorithm is optimal. (2014)

What will be the minimum number of steps needed if we have 5 poles?

What if we have even more poles?

Open problem...

This leads to the "Frame-Stewart conjecture"

**Note:** Another generalization of the original puzzle is to move a given configuration to another. This leads to general shortest path problem, which is hard to compute in general.



# Merge Sort

Given a sequence of  $n$  numbers,  
how many steps are required to sort them into non-decreasing order?

One way to sort the numbers is called the “bubble sort”,  
in which every step we compare two adjacent numbers,  
and make a swap if they are disorder.

This algorithm could take up to roughly  $n^2/2$  steps.

For example, if we are given the reversed sequence  $n, n-1, n-2, \dots, 1$ .

Every time it will search to the end to find the smallest number,  
so the algorithm takes roughly  $(n-1) + (n-2) + \dots + 1 = n(n-1)/2$  steps.

Can we design a faster algorithm?

Think recursively!

# Merge Sort

Suppose we have a program to sort  $n/2$  numbers.

We can use it to sort  $n$  numbers in the following way.

3	8	4	7	2	1	6	5
---	---	---	---	---	---	---	---

Divide the sequence into two halves.

Use the program to sort the two halves independently.

3	4	7	8
---	---	---	---

1	2	5	6
---	---	---	---

With these two sorted sequences of  $n/2$  numbers,  
we can merge them into a sorted sequence of  $n$  numbers easily!

# Merge Sort

**Claim.** Suppose we have two sorted sequences of  $k$  numbers.  
We can merge them into a sorted sequence  
of  $2k$  numbers in  $2k$  steps.

Proof by example:

3 5 7 8 9 10



1 2 4 6 11 12



To decide the smallest number in the two sequences,  
we just need to look at the "heads" of the two sequences.

So, for each step, we can extend the sorted sequence by one number.

So the total number of steps for  $2k$  numbers is  $2k$ .

# Merge Sort

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

3 5 7 8 9 10

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1 2 4 6 11 12

1

1 2

1 2 3

1 2 3 4

1 2 3 4 5

1 2 3 4 5 6

1 2 3 4 5 6 7

1 2 3 4 5 6 7 8

1 2 3 4 5 6 7 8 9

1 2 3 4 5 6 7 8 9 10

1 2 3 4 5 6 7 8 9 10 11

1 2 3 4 5 6 7 8 9 10 11 12

# Merge Sort

Claim. Suppose we have two sorted sequences of  $k$  numbers.  
We can merge them into a sorted sequence  
of  $2k$  numbers in  $2k$  steps.

Suppose we can sort  $k$  numbers in  $T_k$  steps.

Then we can sort  $2k$  numbers in  $2T_k + 2k$  steps.

Therefore,  $T_{2k} = 2T_k + 2k$ . (What if  $n$  is odd?)

If we solve this recurrence (which we will do later),

then we will see that  $T_{2n} \leq n \log_2 n$ .

This is significantly faster than bubble sort!

## Remark

This is an example of the “divide and conquer” algorithm.

This idea is very powerful.

It can be used to design faster algorithms for some basic problems such as integer multiplications, matrix multiplications, etc.

# Plan

- Setting up recurrences
  - Fibonacci recurrence
  - Problem solving recurrences
  - Catalan recurrences
- Solving recurrences

# Parenthesis

How many valid ways to add  $n$  pairs of parentheses?

E.g. There are 5 valid ways to add 3 pairs of parentheses.

$((()))$   $((() ))$   $(())()$   $()(())$   $()()()$

Let  $r_n$  be the number of ways to add  $n$  pairs of parentheses.

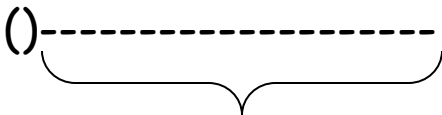
How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



# Parenthesis

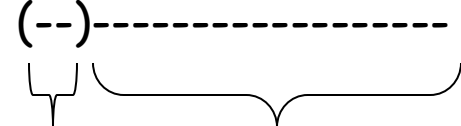
How many valid ways to add  $n$  pairs of parentheses?

Let  $r_n$  be the number of ways to add  $n$  pairs of parentheses.

Case 1:  $()$ -----  


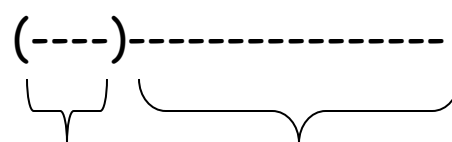
So there are  $r_{n-1}$  in this case.

$r_{n-1}$  ways to add the remaining  $n-1$  pairs.

Case 2:  $(--)$ -----  


So there are  $r_{n-2}$  in this case.

1 way to add 1 pair       $r_{n-2}$  ways to add the remaining  $n-2$  pairs.

Case 3:  $(---)$ -----  


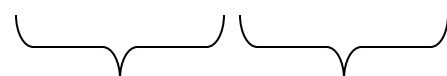
So there are  $2r_{n-3}$  in this case.

2 ways to add 2 pairs       $r_{n-3}$  ways to add the remaining  $n-3$  pairs.

# Parenthesis

How many valid ways to add  $n$  pairs of parentheses?

Let  $r_n$  be the number of ways to add  $n$  pairs of parentheses.

Case  $k$ :  $(\text{-----})\text{-----}$   


$r_{k-1}$  ways to add  $k-1$  pairs  $r_{n-k}$  ways to add the remaining  $n-k$  pairs.

By the product rule, there are  $r_{k-1}r_{n-k}$  ways in case  $k$ .

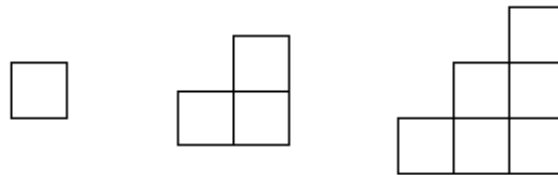
The cases are sorted by the **position** of the close parenthesis of the first open parenthesis, and so these cases are disjoint.

Therefore, by the sum rule, 
$$r_n = \sum_{k=1}^n r_{k-1}r_{n-k}$$

# Stairs

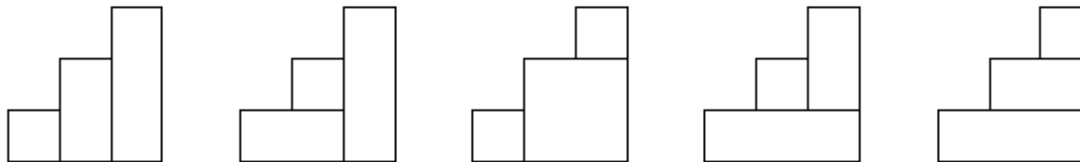
An **n-stair** is the collection of unit squares bounded by x-axis,  $y=x$  and  $x=n+1$ .

For example 1-stair, 2-stair, and 3-stair are like this:



How many ways to fill up the n-stair by exactly n rectangles??

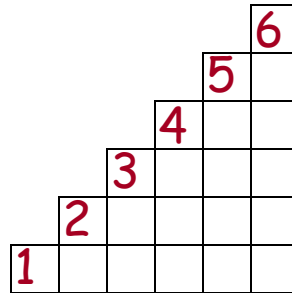
For example, there are 5 ways to fill up the 3-stair by 3 rectangles.



# Stairs

Let  $r_n$  be the number of ways to fill the  $n$ -stair by  $n$  rectangles.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



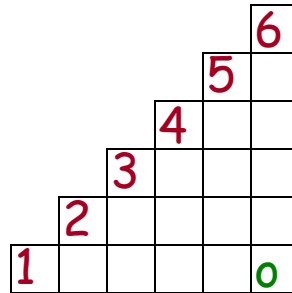
Given the  $n$ -stair, the first observation is that the positions on the diagonal (red numbers) must be covered by different rectangles.

Since there are  $n$  positions in the diagonal and we can only use  $n$  rectangles, each rectangle must cover exactly one red number.

# Stairs

Let  $r_n$  be the number of ways to fill the  $n$ -stair by  $n$  rectangles.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



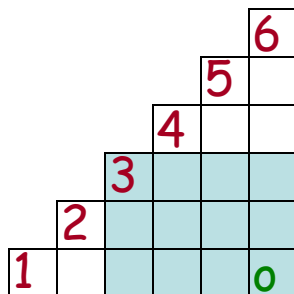
Consider the rectangle **R** that covers the bottom right corner (marked with **0**).

We consider different cases depending on which **red** number is covered by **R**.

# Stairs

Let  $r_n$  be the number of ways to fill the  $n$ -stair by  $n$  rectangles.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



Suppose  $R$  covers  $3$ . Then the 6-stair is divided into 3 parts.

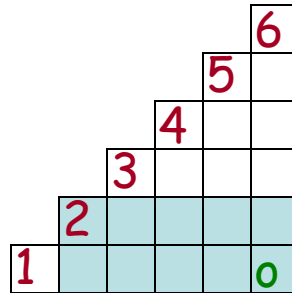
One part is the rectangle **R**. The other two parts are a 2-stair and a 3-stair.

Therefore, in this case, the number of ways to fill in the remaining parts is equal to  $r_2 r_3$

# Stairs

Let  $r_n$  be the number of ways to fill the  $n$ -stair by  $n$  rectangles.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



Similarly suppose  $R$  covers  $2$ .

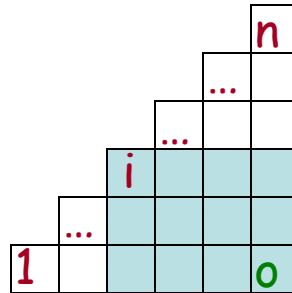
Then the rectangle "breaks" the stair into a 1-stair and a 4-stair.

Therefore, in this case, the number of ways to fill in the remaining parts  
is equal to  $r_1 r_4$

# Stairs

Let  $r_n$  be the number of ways to fill the  $n$ -stair by  $n$  rectangles.

How do we compute it using  $r_1, r_2, \dots, r_{n-1}$ ?



In general suppose the rectangle covers  $i$

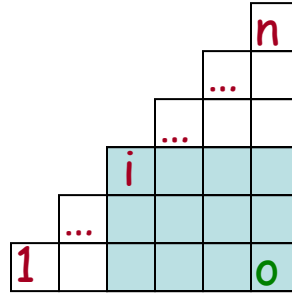
Then the rectangle “breaks” the stair into an  $(i-1)$ -stair and an  $(n-i)$ -stair.

Therefore, in this case, the number of ways to fill in the remaining parts  
is equal to  $r_{i-1}r_{n-i}$  (we define  $r_0=1$ )



# Stairs

The number of ways to fill in the remaining parts is equal to  $r_{i-1}r_{n-i}$



Rectangle **R** covering different **i** will form different configurations, and each configuration must correspond to one of these cases.

Therefore the total number of ways is equal to

$$r_n = \sum_{i=1}^n r_{i-1}r_{n-i}$$

# Catalan Number

How many valid ways to add  $n$  pairs of parentheses?

$$r_n = \sum_{k=1}^n r_{k-1} r_{n-k}$$

So the recursion for the stair problem is the same as the recursion for the parentheses problem. It can be showed that

$$r_n = \frac{1}{n+1} \binom{2n}{n}$$

This is well known as the  **$n$ -th Catalan number**.

# Plan

- Setting up recurrences
  - Fibonacci recurrence
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## Warm Up

$$a_0=1, \quad a_k = a_{k-1} + 2$$

$$a_1 = a_0 + 2$$

$$a_2 = a_1 + 2 = (a_0 + 2) + 2 = a_0 + 4$$

$$a_3 = a_2 + 2 = (a_0 + 4) + 2 = a_0 + 6$$

$$a_4 = a_3 + 2 = (a_0 + 6) + 2 = a_0 + 8$$

See the pattern is  $a_k = a_0 + 2k = 2k+1$

You can verify by induction.

# Solving Hanoi Sequence

$$a_1=1, \quad a_k = 2a_{k-1} + 1$$

$$a_2 = 2a_1 + 1 = 3$$

$$a_3 = 2a_2 + 1 = 2(2a_1 + 1) + 1 = 4a_1 + 3 = 7$$

$$a_4 = 2a_3 + 1 = 2(4a_1 + 3) + 1 = 8a_1 + 7 = 15$$

$$a_5 = 2a_4 + 1 = 2(8a_1 + 7) + 1 = 16a_1 + 15 = 31$$

$$a_6 = 2a_5 + 1 = 2(16a_1 + 15) + 1 = 32a_1 + 31 = 63$$

Guess the pattern is  $a_k = 2^k - 1$

You can verify by induction.

# Solving Merge Sort Recurrence

$$T_{2k} = 2T_k + 2k$$

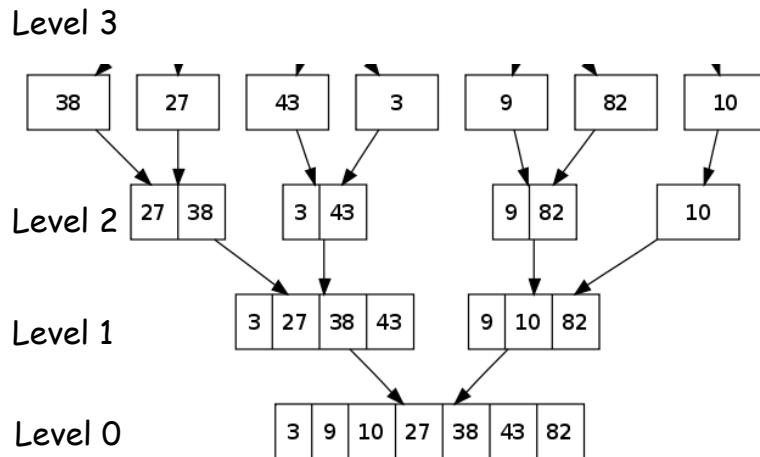
If we could guess that  $T_k = k \log_2 k$ ,  
then we can prove that  $T_{2k} = 2k \log_2(2k)$ .

$$\begin{aligned}\text{This is because } T_{2k} &= 2T_k + 2k \\ &= 2k \log_2 k + 2k \\ &= 2k(\log_2 k + 1) \\ &= 2k(\log_2 k + \log_2 2) \\ &= 2k \log_2 2k\end{aligned}$$

# Solving Merge Sort Recurrence

$$T_{2k} = 2T_k + 2k$$

How could we guess  $T_k = k \log_2 k$ ?



Equality is achieved  
when  $k$  is a power of 2.

$$T_k \leq \log_2 k \cdot k = k \log_2 k$$

#levels

#comparisons  
needed per  
level

= #steps needed to  
sort numbers in  
each merge problem

# Solving Fibonacci Sequence

$$a_0=0, \quad a_1=1, \quad a_n = a_{n-1} + a_{n-2}$$

$$a_2 = a_1 + a_0 = 1$$

$$a_3 = a_2 + a_1 = 2$$

$$a_4 = a_3 + a_2 = 3$$

$$a_5 = a_4 + a_3 = 5$$

$$a_6 = a_5 + a_4 = 8$$

$$a_7 = a_6 + a_5 = 13$$

...

How do we find a formula for  $a_n$  ?



# Generating Functions

$$\langle 0, 0, 0, 0, \dots \rangle \leftrightarrow 0 + 0x + 0x^2 + 0x^3 + \dots = 0$$

$$\langle 1, 1, 1, 1, \dots \rangle \leftrightarrow 1 + x + x^2 + x^3 + \dots = 1/(1-x)$$

$$\langle 1, -1, 1, -1, \dots \rangle \leftrightarrow 1 - x + x^2 - x^3 + \dots = 1/(1+x)$$

$$\langle a_0, a_1, a_2, a_3, \dots \rangle \leftrightarrow F(x)$$

This is called the ordinary generating function for  $\{a_n\}$ :

$$F(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + \dots$$

sequence  $\leftrightarrow$  generating function

# Generating Functions

Scaling:

$$\langle f_0, f_1, f_2, \dots \rangle \longleftrightarrow F(x) \quad \longrightarrow \quad \langle cf_0, cf_1, cf_2, \dots \rangle \longleftrightarrow c \cdot F(x)$$

Addition:

$$\begin{array}{rcl} \langle f_0, f_1, f_2, \dots \rangle & \longleftrightarrow & F(x) \\ + \quad \langle g_0, g_1, g_2, \dots \rangle & \longleftrightarrow & G(x) \\ \hline \langle f_0 + g_0, f_1 + g_1, f_2 + g_2, \dots \rangle & \longleftrightarrow & F(x) + G(x) \end{array}$$

Right shifting:

$$\langle \underbrace{0, 0, \dots, 0}_{k \text{ zeroes}}, f_0, f_1, f_2, \dots \rangle \longleftrightarrow x^k \cdot F(x)$$

Differentiation:

$$\langle f_0, f_1, f_2, f_3, \dots \rangle \longleftrightarrow F(x) \quad \longrightarrow \quad \langle f_1, 2f_2, 3f_3, \dots \rangle \longleftrightarrow F'(x)$$

# Generating Functions

How do we find the generating function for  $\langle 0, 1, 4, 9, \dots \rangle$ ?

$$\langle 1, 1, 1, 1, \dots \rangle \longleftrightarrow \frac{1}{1-x}$$

$$\langle 1, 2, 3, 4, \dots \rangle \longleftrightarrow \frac{d}{dx} \frac{1}{1-x} = \frac{1}{(1-x)^2}$$

$$\langle 0, 1, 2, 3, \dots \rangle \longleftrightarrow x \cdot \frac{1}{(1-x)^2} = \frac{x}{(1-x)^2}$$

$$\langle 1, 4, 9, 16, \dots \rangle \longleftrightarrow \frac{d}{dx} \frac{x}{(1-x)^2} = \frac{1+x}{(1-x)^3}$$

$$\langle 0, 1, 4, 9, \dots \rangle \longleftrightarrow x \cdot \frac{1+x}{(1-x)^3} = \frac{x(1+x)}{(1-x)^3}$$

So the generating function is

$$\boxed{\frac{x(1+x)}{(1-x)^3}}$$

# Solving Fibonacci Sequence

How does generating function help solve Fibonacci sequence ?

Fibonacci sequence:  $f_0=0$ ,  $f_1=1$ ,  $f_n = f_{n-1} + f_{n-2}$

So the generating function for  $\{f_n\}$  is

$$F(x) = f_0 + f_1x + f_2x^2 + f_3x^3 + \dots = 0 + x + (f_1 + f_0)x^2 + (f_2 + f_1)x^3 + \dots$$

We can find the generating function for  $\langle 0, 1, f_1 + f_0, f_2 + f_1, \dots \rangle$  !

$$\begin{array}{rcl}
 \langle 0, & 1, & 0, & 0, & 0, & \dots \rangle & \longleftrightarrow & x \\
 \langle 0, & f_0, & f_1, & f_2, & f_3, & \dots \rangle & \longleftrightarrow & xF(x) \\
 + \quad \langle 0, & 0, & f_0, & f_1, & f_2, & \dots \rangle & \longleftrightarrow & x^2F(x) \\
 \hline
 \langle 0, & 1 + f_0, & f_1 + f_0, & f_2 + f_1, & f_3 + f_2, & \dots \rangle & \longleftrightarrow & x + xF(x) + x^2F(x)
 \end{array}$$

$$F(x) = x + xF(x) + x^2F(x)$$

# Solving Fibonacci Sequence

Resolving  $F(x)$  we get:

$$F(x) = x/(1-x-x^2)$$

Partial fractioning gives:

$$F(x) = \frac{1}{\sqrt{5}} \left( \frac{1}{1 - \alpha_1 x} - \frac{1}{1 - \alpha_2 x} \right)$$

where  $\alpha_1 = \frac{1}{2}(1 + \sqrt{5})$  and  $\alpha_2 = \frac{1}{2}(1 - \sqrt{5})$ .

Expand  $F(x)$  using Taylor series:

$$F(x) = \frac{1}{\sqrt{5}} ((1 + \alpha_1 x + \alpha_1^2 x^2 + \dots) - (1 + \alpha_2 x + \alpha_2^2 x^2 + \dots))$$



$$f_n = \frac{\alpha_1^n - \alpha_2^n}{\sqrt{5}} = \frac{1}{\sqrt{5}} \left( \left( \frac{1 + \sqrt{5}}{2} \right)^n - \left( \frac{1 - \sqrt{5}}{2} \right)^n \right)$$

## Second Order Recurrence Relation

It seems that we do something more general like:

$$a_k = Aa_{k-1} + Ba_{k-2}$$

A and B are real numbers and  $B \neq 0$

This is called "second-order linear homogeneous recurrence relation with constant coefficients".

For example, Fibonacci sequence is when  $A=B=1$ .

Can we give a general answer to this problem ?

## Distinct-Roots Theorem

Suppose a sequence  $(a_0, a_1, a_2, a_3, \dots)$  satisfies a recurrence relation

$$a_k = Aa_{k-1} + Ba_{k-2}$$

If  $t^2 - At - B = 0$  has two *distinct* roots  $r$  and  $s$ ,

then  $a_n = Cr^n + Ds^n$  for some  $C$  and  $D$ .

The theorem says that any solution of the recurrence relation is a linear combination of the two series  $(1, r, r^2, r^3, r^4, \dots, r^n, \dots)$  and  $(1, s, s^2, s^3, s^4, \dots, s^n, \dots)$  defined by the distinct roots of  $t^2 - At - B = 0$ .

So, if  $a_0$  and  $a_1$  are given, then  $C$  and  $D$  are uniquely determined.

## Example

$$a_n = a_{n-1} + 2a_{n-2}$$

Need to find solutions of the form  $(1, t, t^2, t^3, t^4, \dots, t^n, \dots)$

where  $t$  is a root of the quadratic equation  $t^2 - t - 2 = 0$ .

This implies that  $r=2$  or  $s=-1$ .

If we did not know  $a_0, a_1$ , they are many solutions for  $\{a_n\}$ :

(i)  $(1, 2, 4, 8, 16, 32, 64, \dots)$

$$a_n = r^n$$

(ii)  $(1, -1, 1, -1, 1, -1, \dots)$

$$a_n = s^n$$

(iii)  $(2, 1, 5, 7, 17, 31, 65, \dots)$

$$a_n = r^n + s^n$$

(iv) ...

...



# Revisiting Fibonacci Sequence

If  $a_0, a_1$  are given...

$$a_0=0, \quad a_1=1, \quad a_n = a_{n-1} + a_{n-2}$$

First solve the quadratic equation  $t^2 - t - 1 = 0$ .

$$t = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

So the distinct roots are:

$$r = \frac{1 + \sqrt{5}}{2} \quad s = \frac{1 - \sqrt{5}}{2}$$

## Revisiting Fibonacci Sequence

$$a_0=0, \quad a_1=1, \quad a_n = a_{n-1} + a_{n-2}$$

By the distinct-roots theorem, the solutions satisfy the formula:

$$a_n = C\left(\frac{1 + \sqrt{5}}{2}\right)^n + D\left(\frac{1 - \sqrt{5}}{2}\right)^n$$

To figure out  $C$  and  $D$ , we substitute the value of  $a_0$  and  $a_1$ :

$$0 = C + D$$

$$1 = C\left(\frac{1 + \sqrt{5}}{2}\right) + D\left(\frac{1 - \sqrt{5}}{2}\right)$$

## Revisiting Fibonacci Sequence

Solving these two equations, we get:

$$C = \frac{1}{\sqrt{5}}, D = -\frac{1}{\sqrt{5}}$$

Therefore:

$$\begin{aligned} a_n &= C\left(\frac{1 + \sqrt{5}}{2}\right)^n + D\left(\frac{1 - \sqrt{5}}{2}\right)^n \\ &= \frac{1}{\sqrt{5}}\left(\frac{1 + \sqrt{5}}{2}\right)^n - \frac{1}{\sqrt{5}}\left(\frac{1 - \sqrt{5}}{2}\right)^n \end{aligned}$$

# Quick Summary

Recursion is a very useful technique in computer science.

It is very important to learn to think recursively, by reducing the problem into smaller problems.

This is an essential skill to acquire if one wants to become a professional programmer.

Make sure you have more practice in setting up recurrence relations and generating functions.