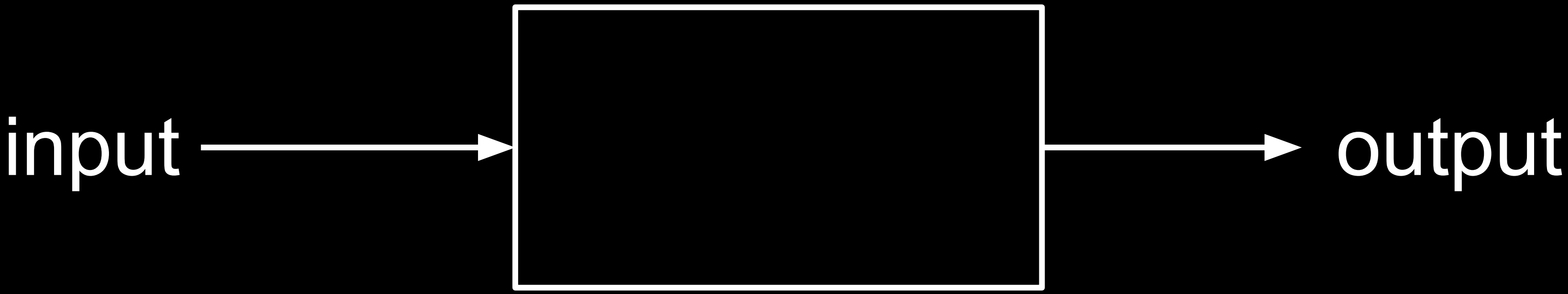
ALGORITHMS

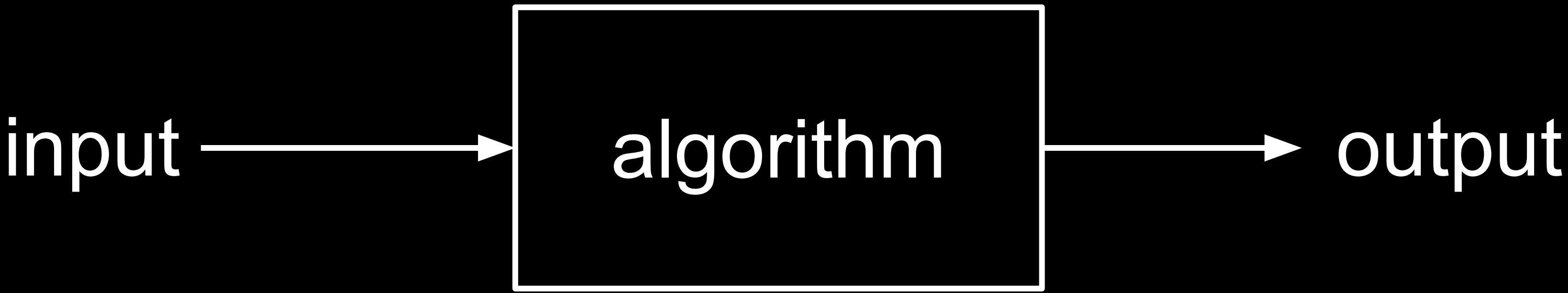
BACK

what solves the problem?



input

output



input

algorithm

output

algorithm, program, process

"A finitely long rule consisting of individual instructions is called an algorithm."

Source: Vornberger, O., Algorithmen und Datenstrukturen, Lecture notes: http://www-lehre.inf.uos.de/~ainf/2013/PDF/skript.pdf

"A program is an algorithm expressed in a programming language."

Source: Vornberger, O., Algorithmen und Datenstrukturen, Lecture notes: http://www-lehre.inf.uos.de/~ainf/2013/PDF/skript.pdf

"A process is a program that is currently executed by a computer."

Source: Vornberger, O., Algorithmen und Datenstrukturen, Lecture notes: http://www-lehre.inf.uos.de/~ainf/2013/PDF/skript.pdf

input
?
output

greatest common divisor

euclidean algorithm

Identify the larger number. If a < b, swap numbers so that a > b

Subtract b from a and replace a with the result

Repeat until one of the numbers becomes 0

Return the number that is not zero

```
Loop 1:
a = 18, b = 48 → swap
```

Loop 1:

a = 18, b = 48 → swap → a = 48, b = 18

a = 48 - 18 = 30

```
Loop 1:
a = 18, b = 48 → swap → a = 48, b = 18
a = 48 - 18 = 30

Loop 2:
a = 30, b = 18 → no swap
a = 30 - 18 = 12
```

```
Loop 1:
a = 18, b = 48 → swap → a = 48, b = 18
a = 48 - 18 = 30

Loop 2:
a = 30, b = 18 → no swap
a = 30 - 18 = 12

Loop 3:
a = 12, b = 18 → swap → a = 18, b = 12
a = 18 - 12 = 6
```

```
Loop 1:
a = 18, b = 48 → swap → a = 48, b = 18
a = 48 - 18 = 30

Loop 2:
a = 30, b = 18 → no swap
a = 30 - 18 = 12

Loop 3:
a = 12, b = 18 → swap → a = 18, b = 12
a = 18 - 12 = 6

Loop 4:
a = 6, b = 12 → swap → a = 12, b = 6
a = 12 - 6 = 6
```

```
Loop 1:
a = 18, b = 48 ⟶ swap ⟶ a = 48, b = 18
a = 48 - 18 = 30

Loop 2:
a = 30, b = 18 ⟶ no swap
a = 30 - 18 = 12

Loop 3:
a = 12, b = 18 ⟶ swap ⟶ a = 18, b = 12
a = 18 - 12 = 6

Loop 4:
a = 6, b = 12 ⟶ swap ⟶ a = 12, b = 6
a = 12 - 6 = 6

Loop 5:
a = 6, b = 6 ⟶ no swap
a = 6 - 6 = 0
```

```
Loop 1:
a = 18, b = 48 ⟶ swap ⟶ a = 48, b = 18
a = 48 - 18 = 30

Loop 2:
a = 30, b = 18 ⟶ no swap
a = 30 - 18 = 12

Loop 3:
a = 12, b = 18 ⟶ swap ⟶ a = 18, b = 12
a = 18 - 12 = 6

Loop 4:
a = 6, b = 12 ⟶ swap ⟶ a = 12, b = 6
a = 12 - 6 = 6

Loop 5:
a = 6, b = 6 ⟶ no swap
a = 6 - 6 = 0

return b = 6
```

algorithm representation

100 Good Cookies

1 cup white sugar
1 cup brown sugar
1 cup margarine
1 cup cooking oil
1 egg
1 teaspoon vanilla
1 teaspoon cream of tartar

1 teaspoon baking soda
1 cup quick oatmeal
1 cup coconut
1 cup Rice Krispies
1 cup chopped walnuts
3½ cups flour
1-12oz. package mini Chocolate chips

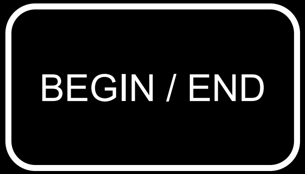
Mix in order given. Drop by teaspoonful onto cookie sheet. Bake at 350° for 8-10 minutes.

(over)

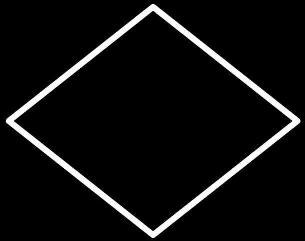
pseudocode

```
READ a, b

REPEAT

    IF a < b THEN
        a = b
        b = a

    a = a - b

UNTIL a = 0 OR b = 0

RETURN the variable that is not 0
```

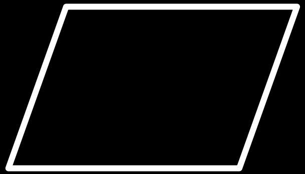
flow diagrams



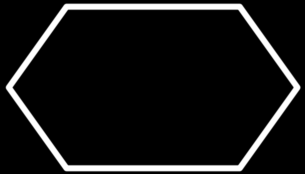
start / end of algorithm



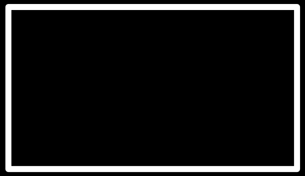
decision



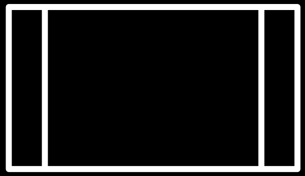
input / output



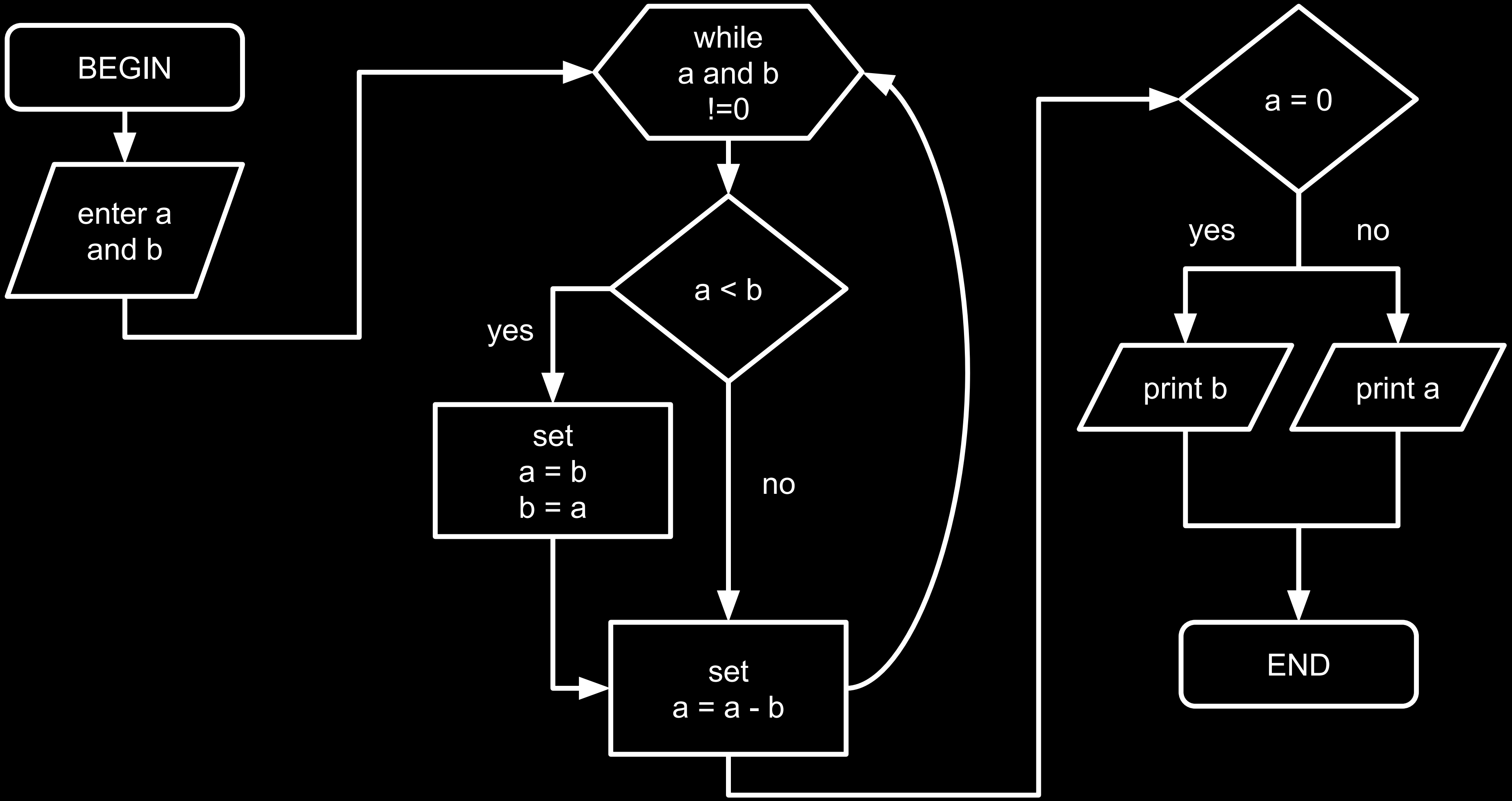
repetition



command / assignment



external routine


BEGIN
enter a and b
while a and b !=0
a < b
yes
set a = b b = a
no
set a = a - b
a = 0
yes
no
print b
print a
END

input

?

output

square roots

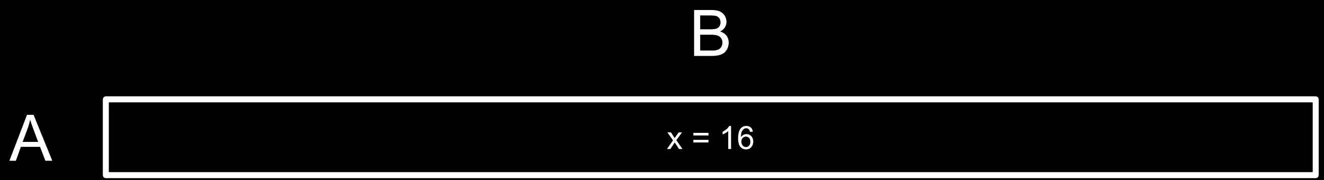
babylonian method

calculate square root of

$x = 16$

$A = 1$

$B = x / A = 16$



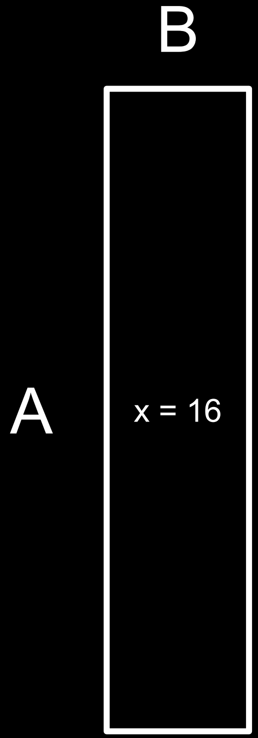
B

A

x = 16

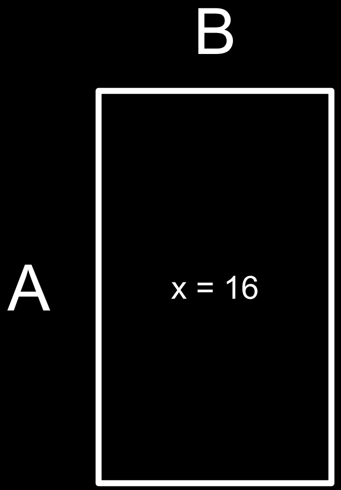
$$A = (A + B) / 2 = 17 / 2 = 8.5$$

$$B = x / A = 16 / 8.5 \approx 1.88$$



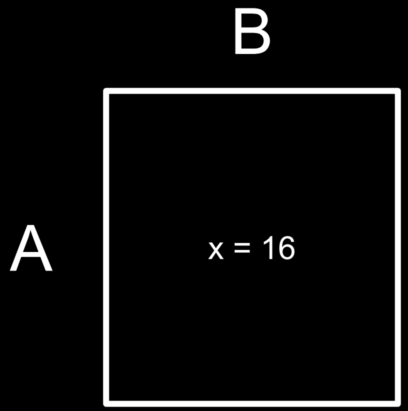
$$A = (A + B) / 2 \approx 10.38 / 2 \approx 5.19$$

$$B = x / A \approx 16 / 5.19 \approx 3.08$$



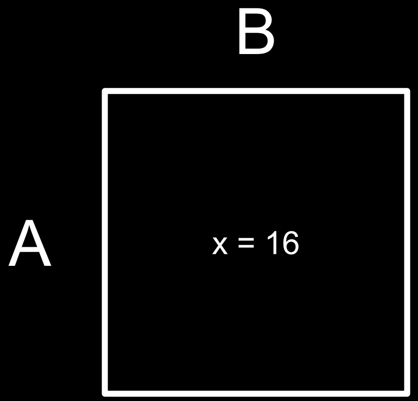
$$A = (A + B) / 2 \approx 8.27 / 2 \approx 4.14$$

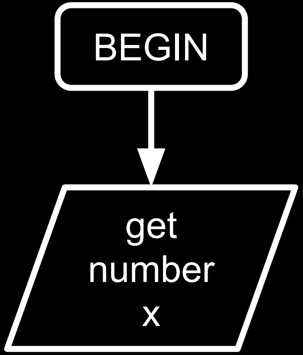
$$B = x / A \approx 16 / 4.14 \approx 3.86$$

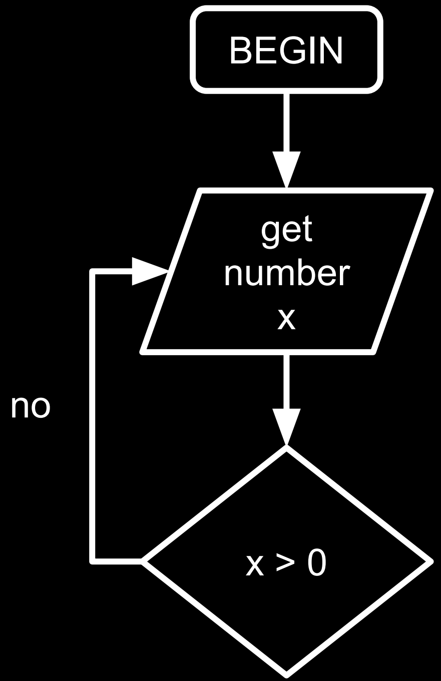


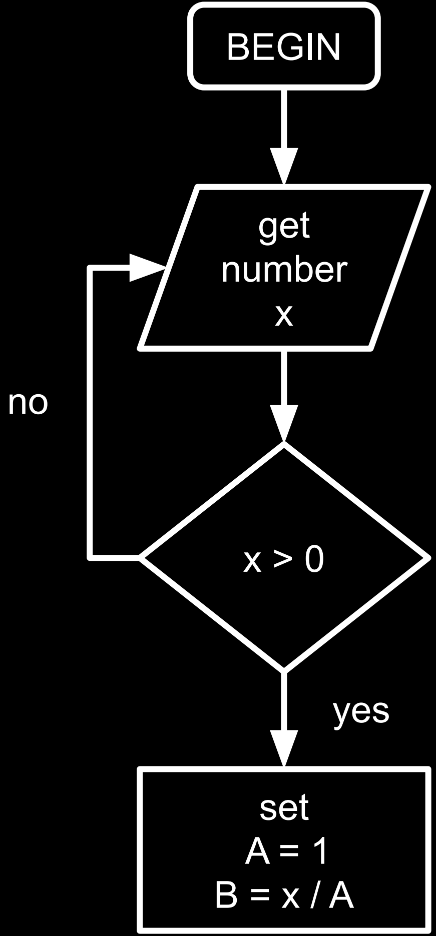
$A = (A + B) / 2 = 8 / 2 = \mathbf{4}$

$B = x / A = 16 / 4 = \mathbf{4}$




BEGIN
get number x


BEGIN
get number x
no
x > 0



BEGIN

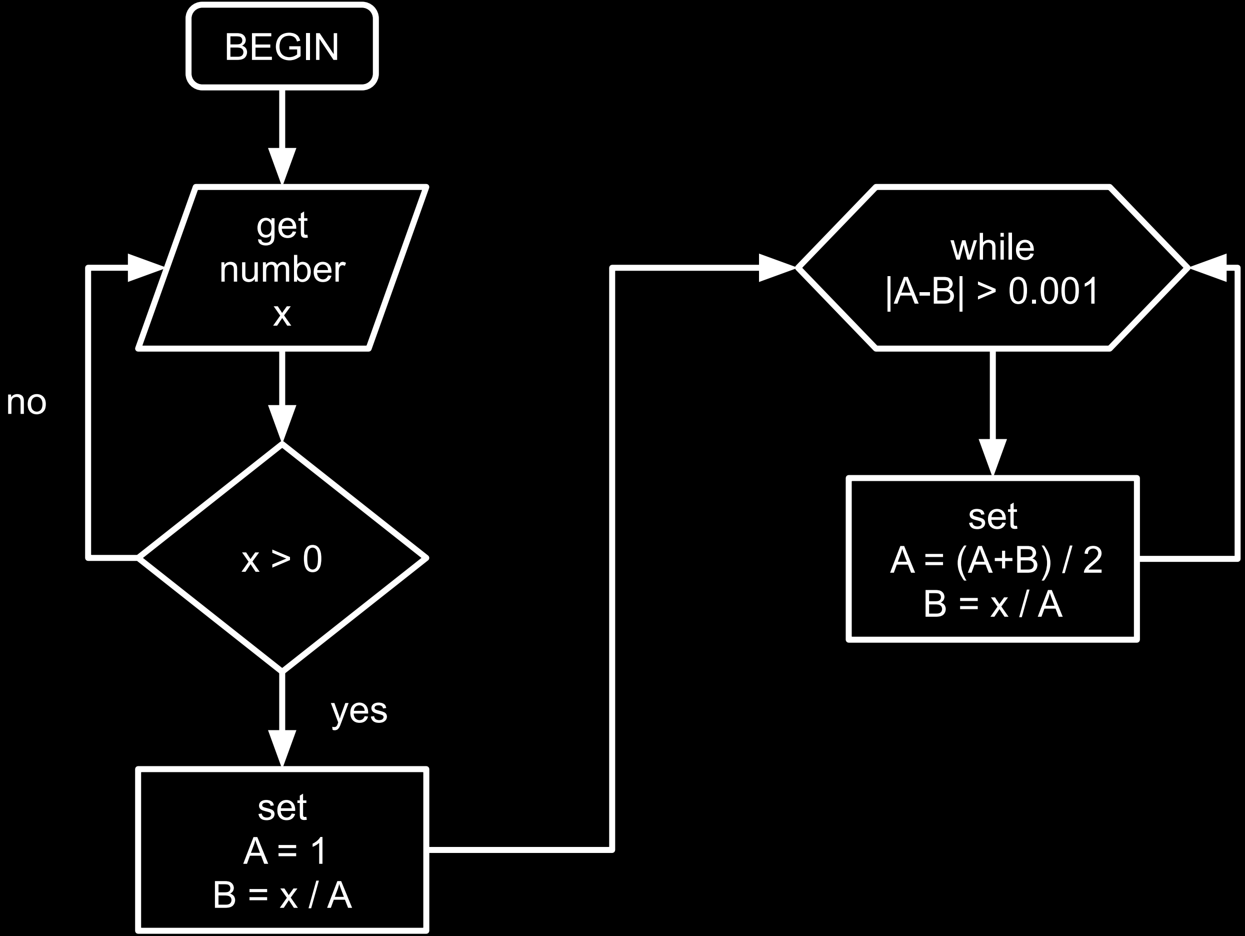
get number x

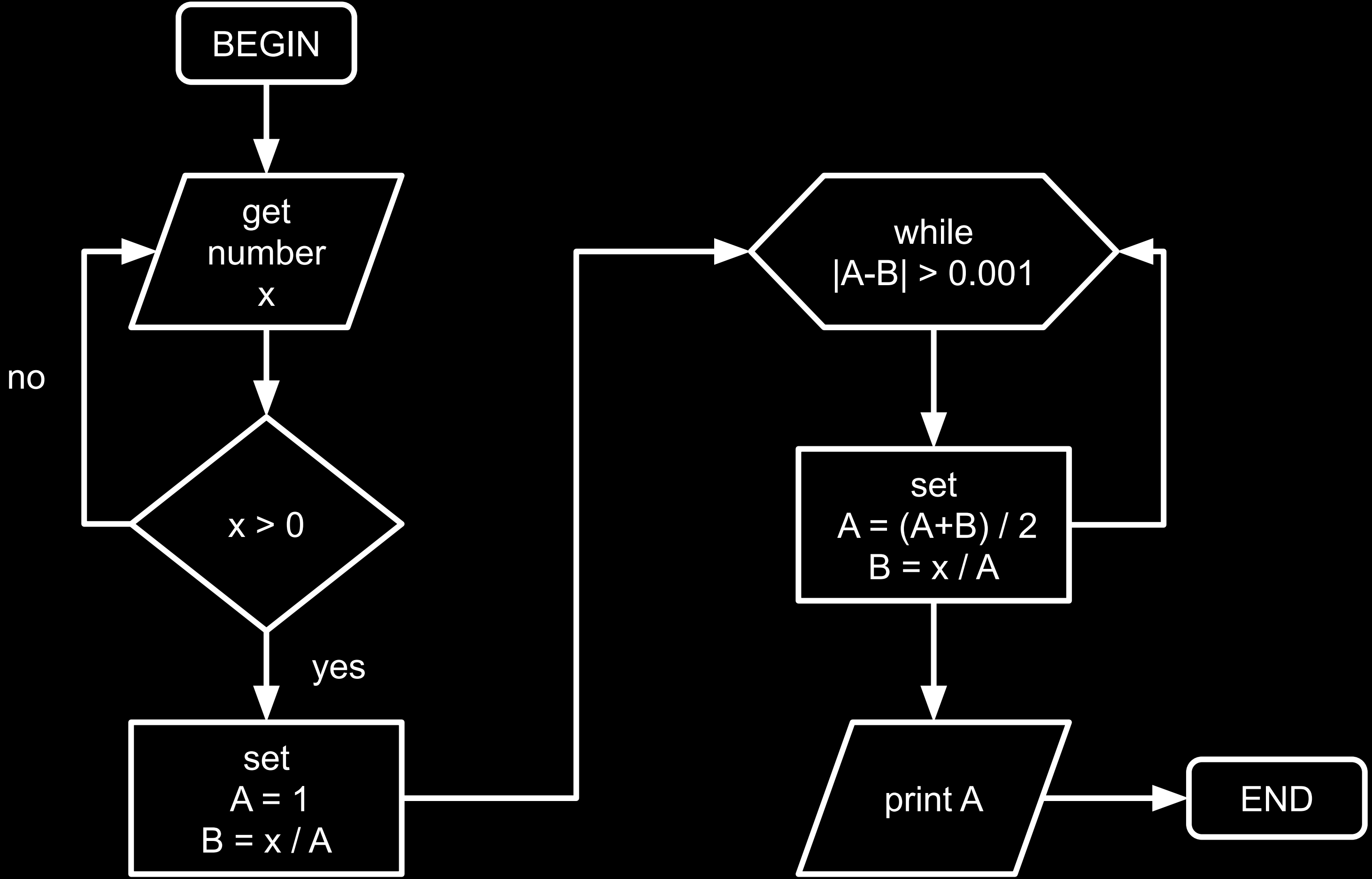
x > 0

no

yes

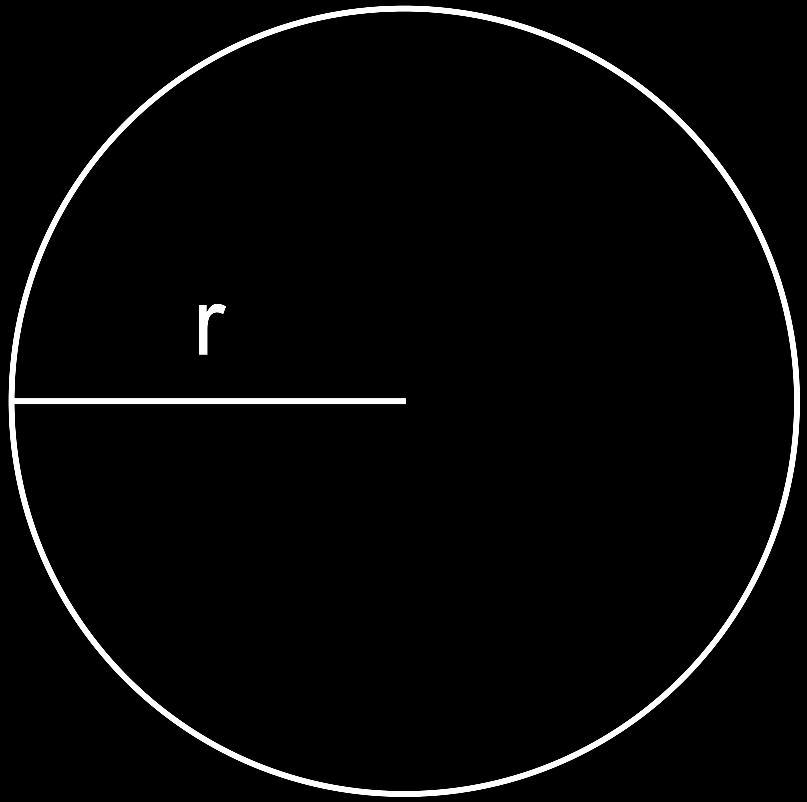
set
A = 1
B = x / A

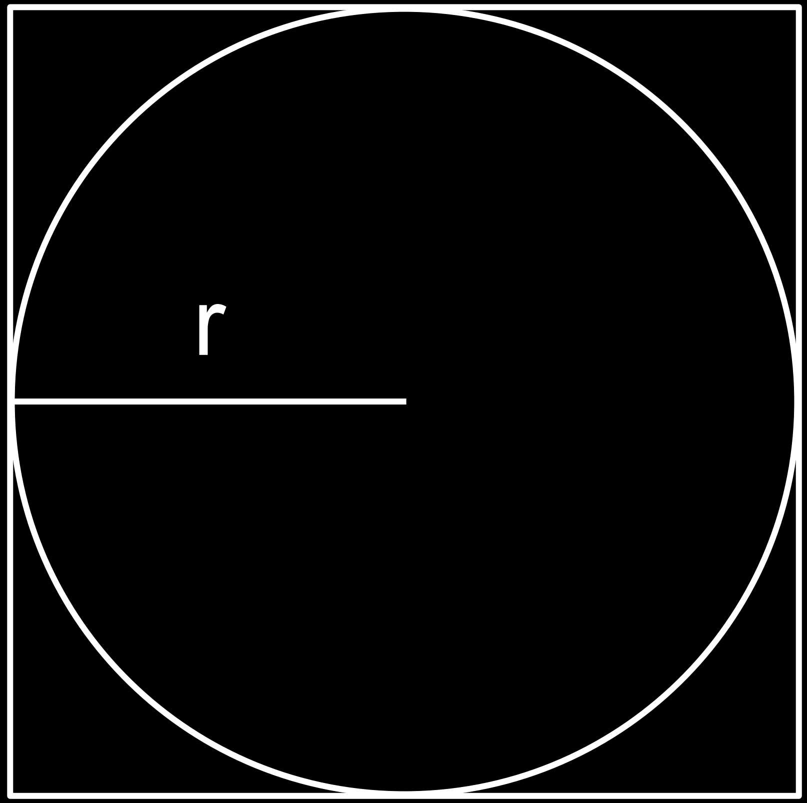

BEGIN
get number x
no
x > 0
yes
set
A = 1
B = x / A
while
|A-B| > 0.001
set
A = (A+B) / 2
B = x / A

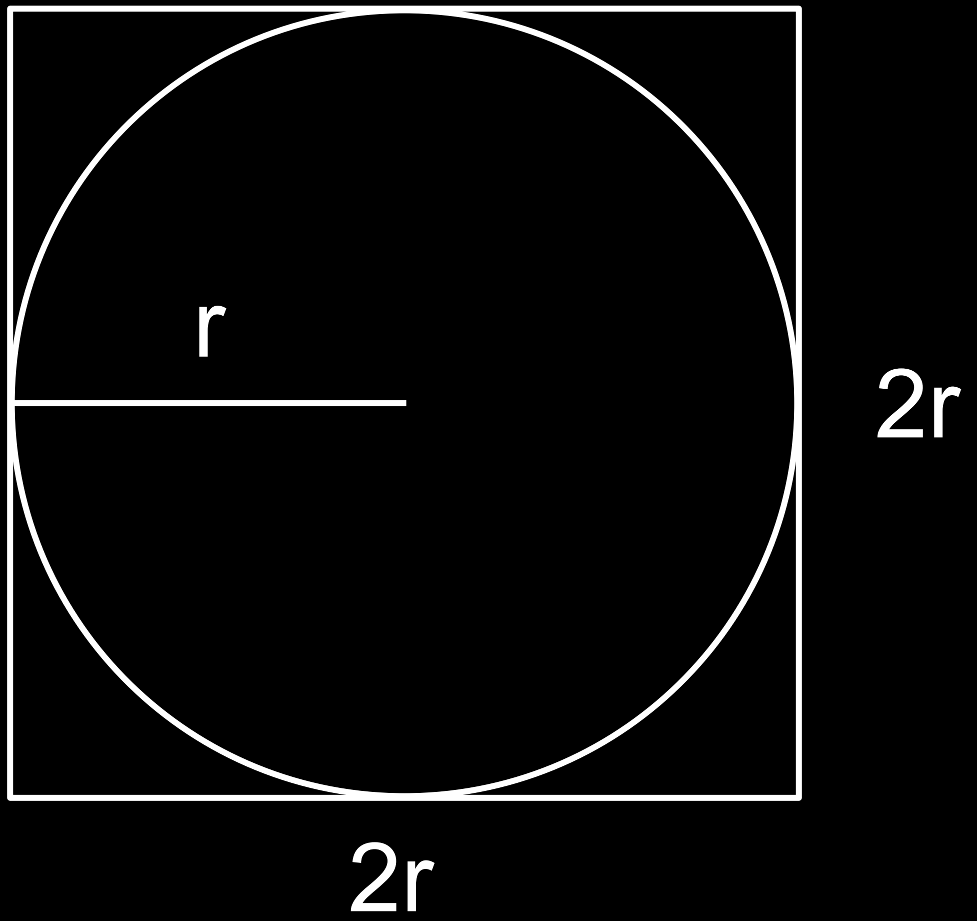

BEGIN
get number x
no
x > 0
yes
set
A = 1
B = x / A
while
|A-B| > 0.001
set
A = (A+B) / 2
B = x / A
print A
END

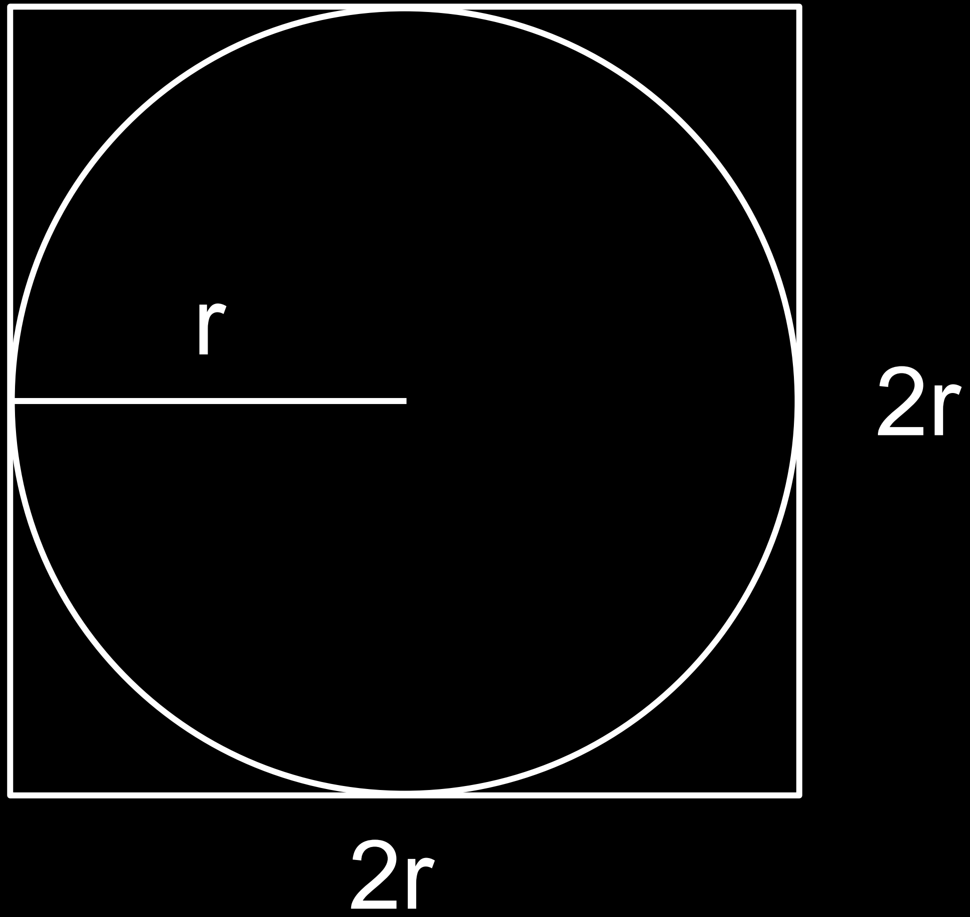
input
?
output

estimating π

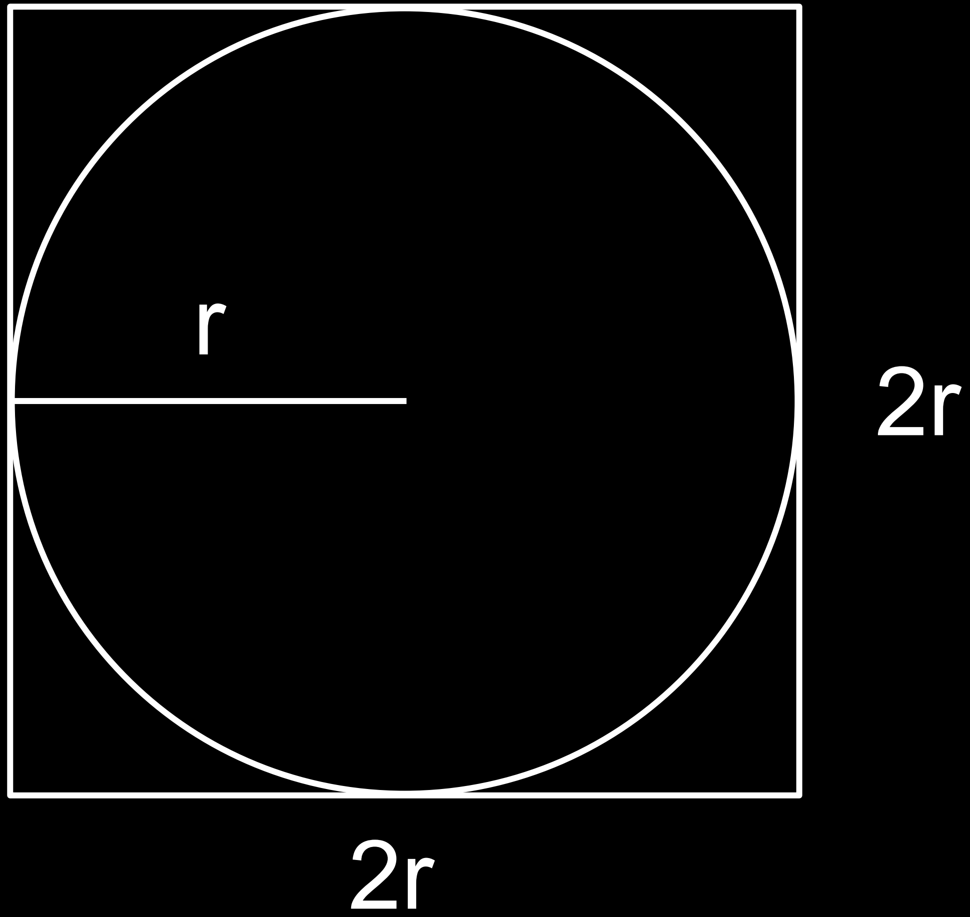

r


r

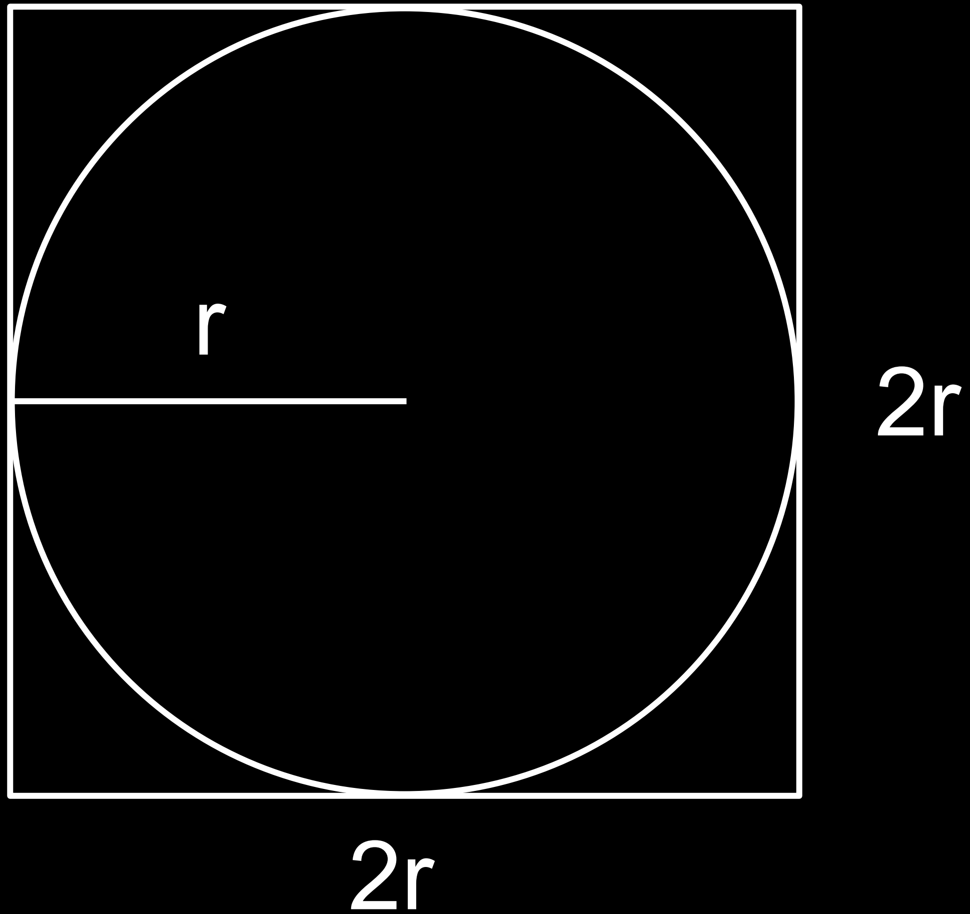

r
2r
2r



$$\frac{\bigcirc}{\square} = \frac{\pi r^2}{4r^2}$$

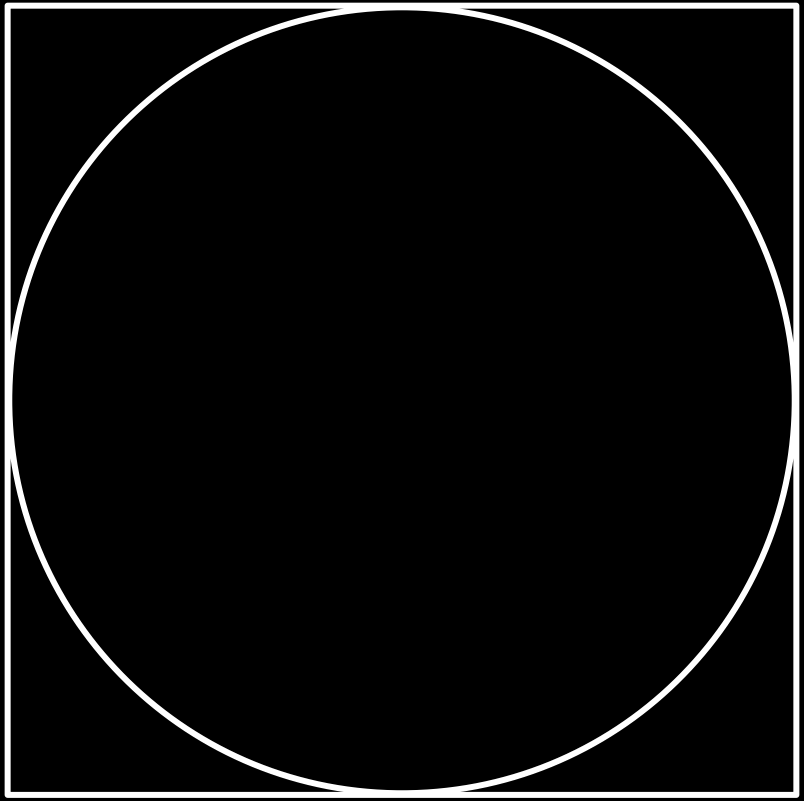


$$\frac{\bigcirc}{\square} = \frac{\pi\cancel{r^2}}{4\cancel{r^2}}$$

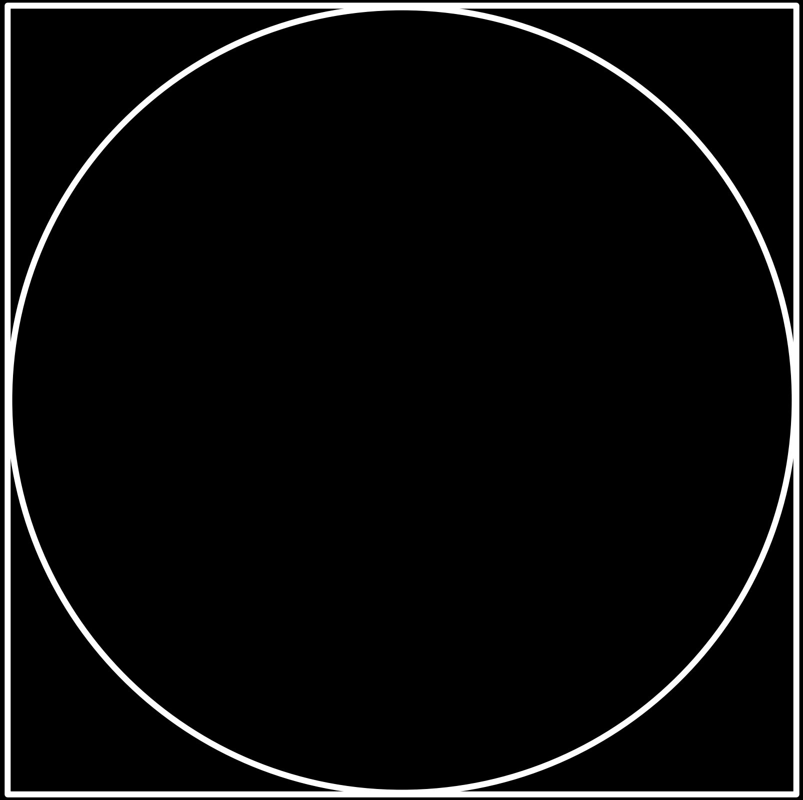


$$\frac{\bigcirc}{\square} = \frac{\pi}{4}$$

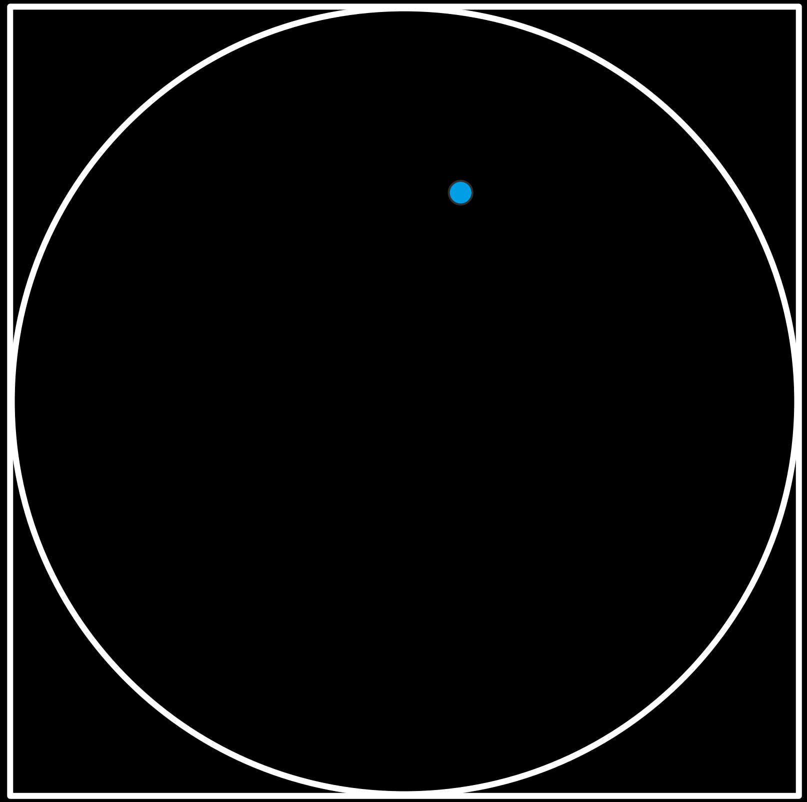
monte carlo simulation



$$\frac{\bigcirc}{\square} = \frac{\pi}{4}$$

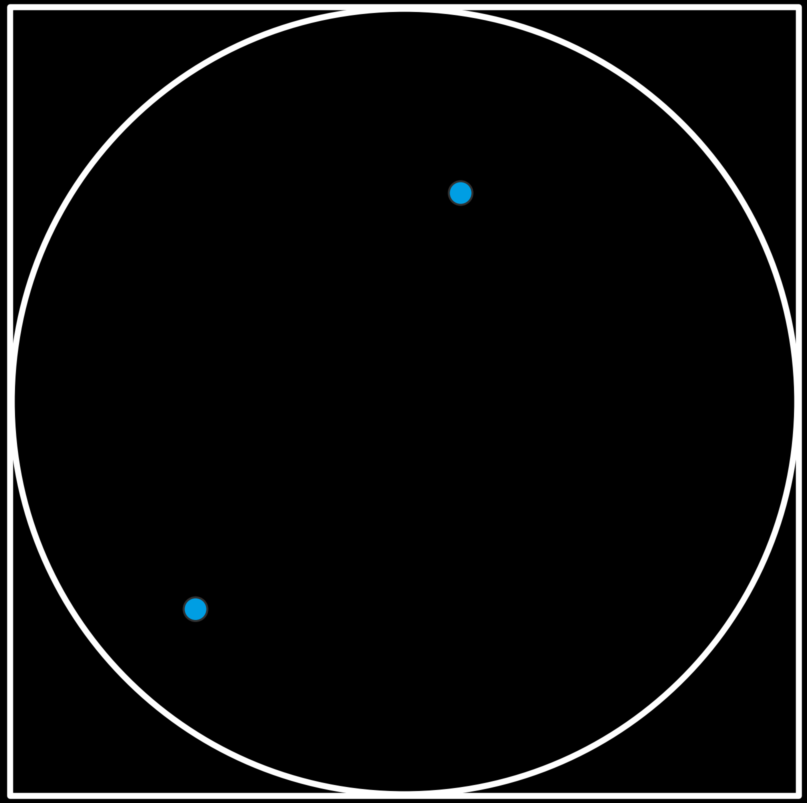


$$4\,\frac{\bigcirc}{\square} = \pi$$



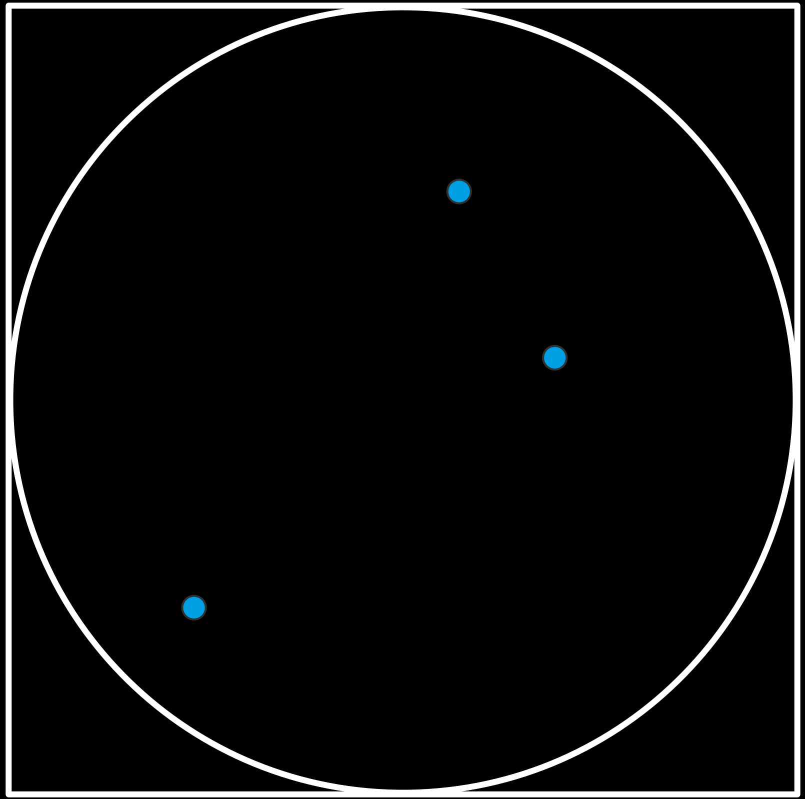
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 4$$



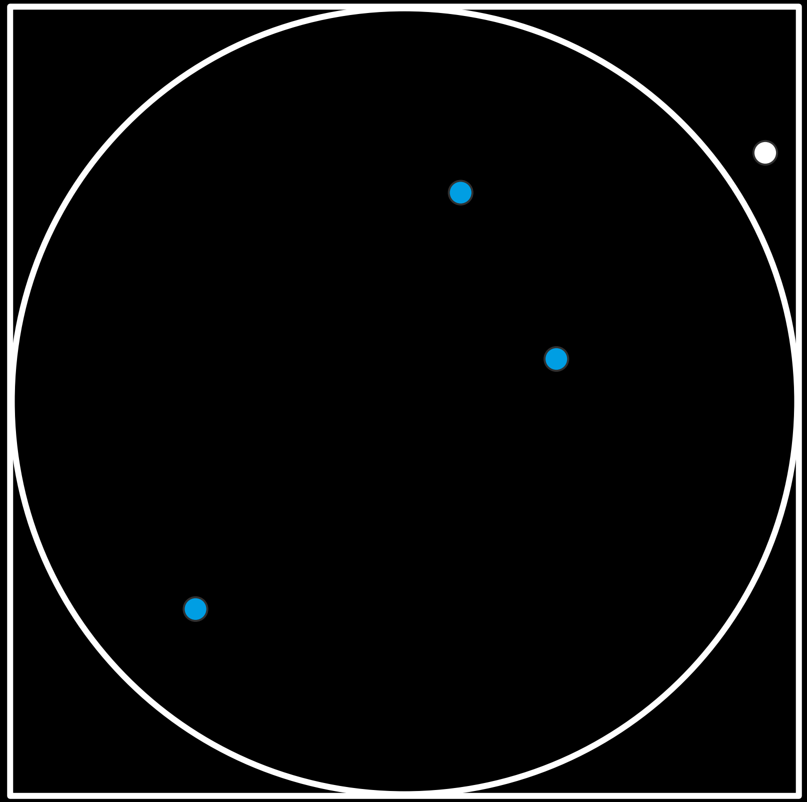
$$4\,\frac{○}{□} = \pi$$

$$= 4$$



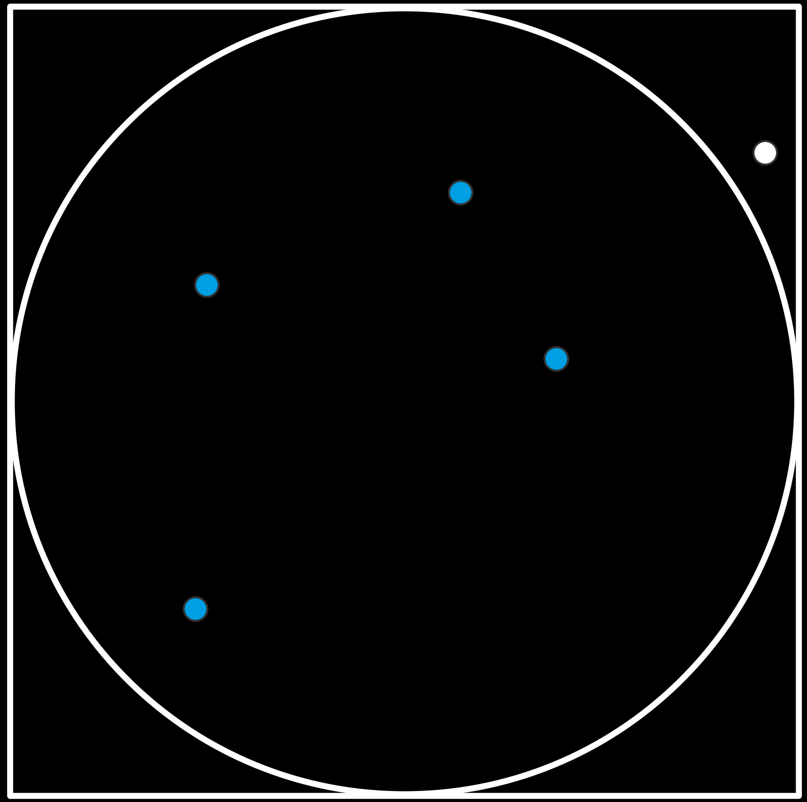
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 4$$



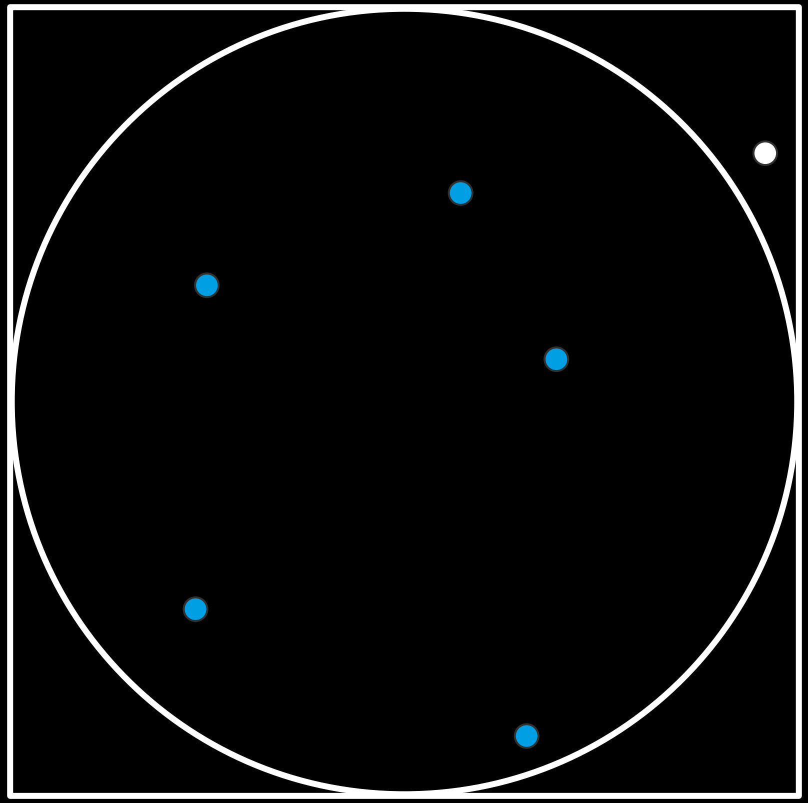
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 3$$



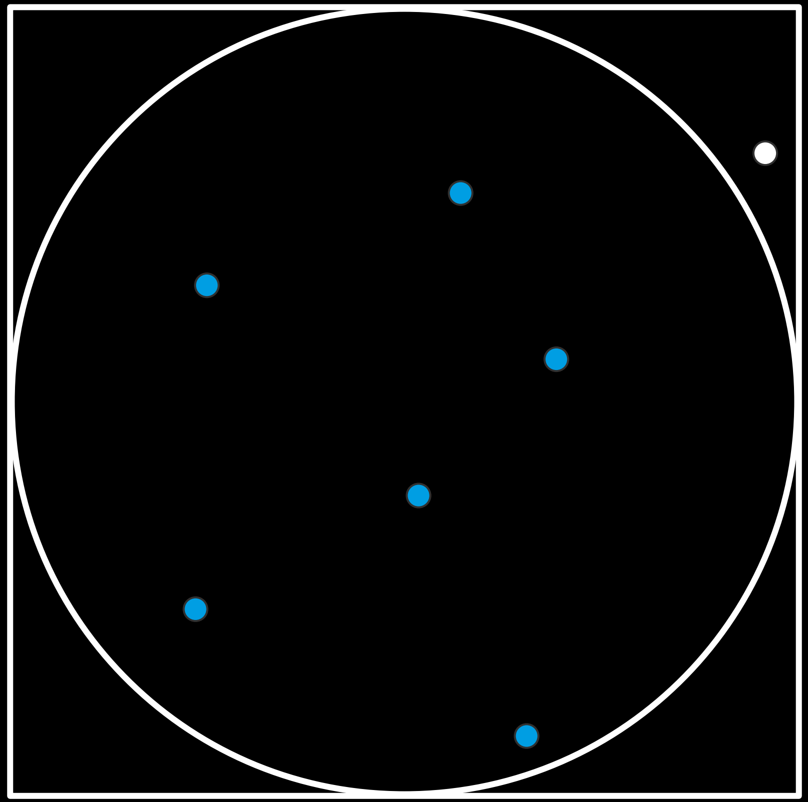
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 3{,}2$$



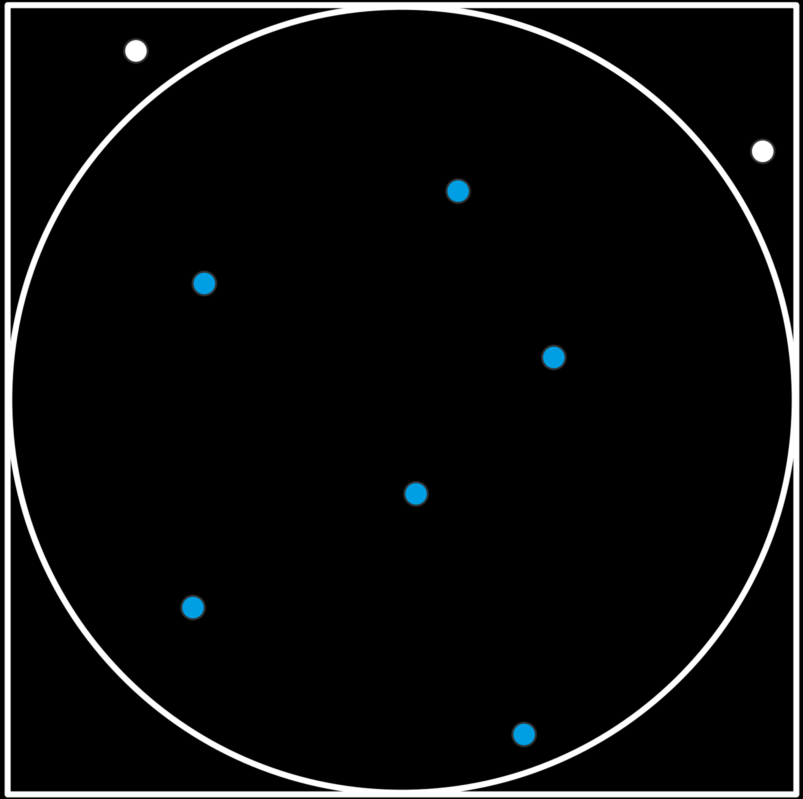
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 3{,}33$$



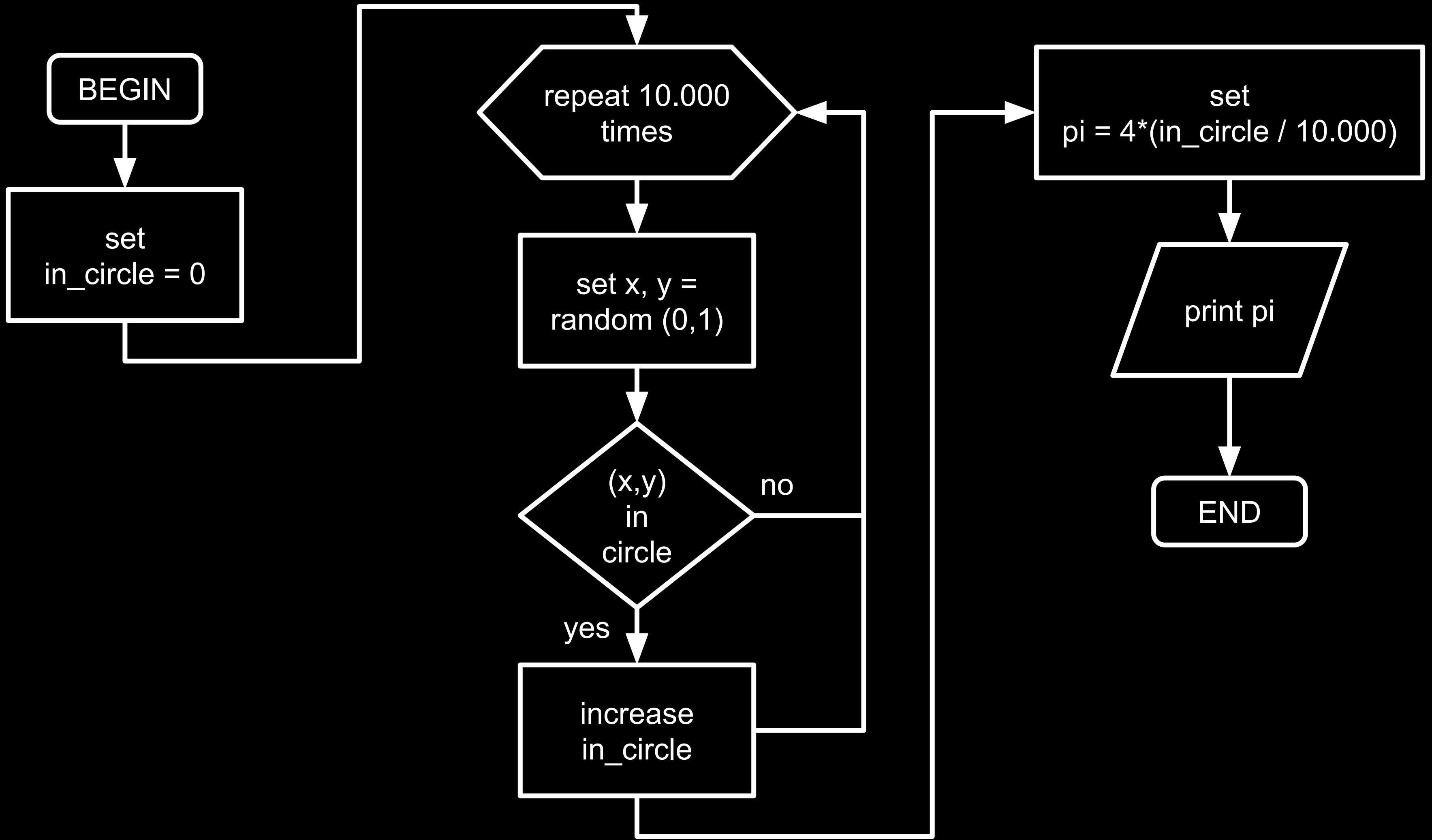
$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 3{,}43$$



$$4\,\frac{\bigcirc}{\square} = \pi$$

$$= 3$$


BEGIN
set
in_circle = 0
repeat 10.000
times
set x, y =
random (0,1)
(x,y)
in
circle
no
yes
increase
in_circle
set
pi = 4*(in_circle / 10.000)
print pi
END

gregory-leibniz series

$$\pi = 4\sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1}$$

$$\pi = 4(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \frac{1}{11} + \ldots)$$

input
?
output

sorting

[9, 5, 2, 1, 4, 7]

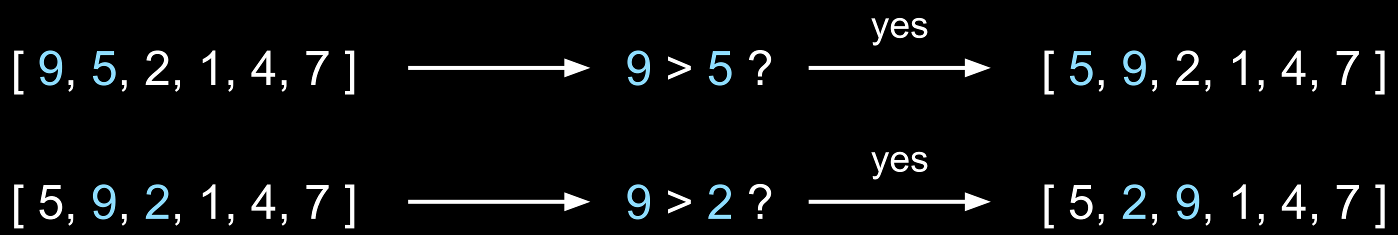
bubble sort

repeatedly compare and swap elements
until done.

[9, 5, 2, 1, 4, 7]

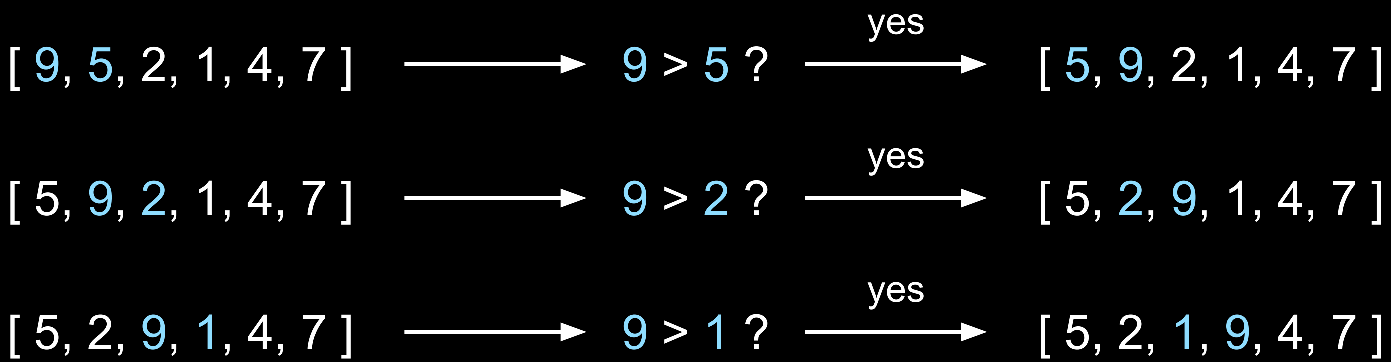
[9, 5, 2, 1, 4, 7] → 9 > 5 ?

$$[\,9, 5, 2, 1, 4, 7\,] \xrightarrow{\quad} 9 > 5\,? \xrightarrow{\text{yes}} [\,5, 9, 2, 1, 4, 7\,]$$



[9, 5, 2, 1, 4, 7] → 9 > 5 ? → yes → [5, 9, 2, 1, 4, 7]

[5, 9, 2, 1, 4, 7] → 9 > 2 ? → yes → [5, 2, 9, 1, 4, 7]



[9, 5, 2, 1, 4, 7] → 9 > 5 ? → yes → [5, 9, 2, 1, 4, 7]

[5, 9, 2, 1, 4, 7] → 9 > 2 ? → yes → [5, 2, 9, 1, 4, 7]

[5, 2, 9, 1, 4, 7] → 9 > 1 ? → yes → [5, 2, 1, 9, 4, 7]

$$[\ 9, 5, 2, 1, 4, 7\ ] \longrightarrow 9 > 5\ ? \xrightarrow{\text{yes}} [\ 5, 9, 2, 1, 4, 7\ ]$$

$$[\ 5, 9, 2, 1, 4, 7\ ] \longrightarrow 9 > 2\ ? \xrightarrow{\text{yes}} [\ 5, 2, 9, 1, 4, 7\ ]$$

$$[\ 5, 2, 9, 1, 4, 7\ ] \longrightarrow 9 > 1\ ? \xrightarrow{\text{yes}} [\ 5, 2, 1, 9, 4, 7\ ]$$

$$[\ 5, 2, 1, 9, 4, 7\ ] \longrightarrow 9 > 4\ ? \xrightarrow{\text{yes}} [\ 5, 2, 1, 4, 9, 7\ ]$$

$$[\ 9,\ 5,\ 2,\ 1,\ 4,\ 7\ ] \longrightarrow 9 > 5\ ? \xrightarrow{\text{yes}} [\ 5,\ 9,\ 2,\ 1,\ 4,\ 7\ ]$$

$$[\ 5,\ 9,\ 2,\ 1,\ 4,\ 7\ ] \longrightarrow 9 > 2\ ? \xrightarrow{\text{yes}} [\ 5,\ 2,\ 9,\ 1,\ 4,\ 7\ ]$$

$$[\ 5,\ 2,\ 9,\ 1,\ 4,\ 7\ ] \longrightarrow 9 > 1\ ? \xrightarrow{\text{yes}} [\ 5,\ 2,\ 1,\ 9,\ 4,\ 7\ ]$$

$$[\ 5,\ 2,\ 1,\ 9,\ 4,\ 7\ ] \longrightarrow 9 > 4\ ? \xrightarrow{\text{yes}} [\ 5,\ 2,\ 1,\ 4,\ 9,\ 7\ ]$$

$$[\ 5,\ 2,\ 1,\ 4,\ 9,\ 7\ ] \longrightarrow 9 > 7\ ? \xrightarrow{\text{yes}} [\ 5,\ 2,\ 1,\ 4,\ 7,\ 9\ ]$$

$$[\,5, 2, 1, 4, 7, 9\,] \longrightarrow 5 > 2\ ? \xrightarrow{\text{yes}} [\,2, 5, 1, 4, 7, 9\,]$$

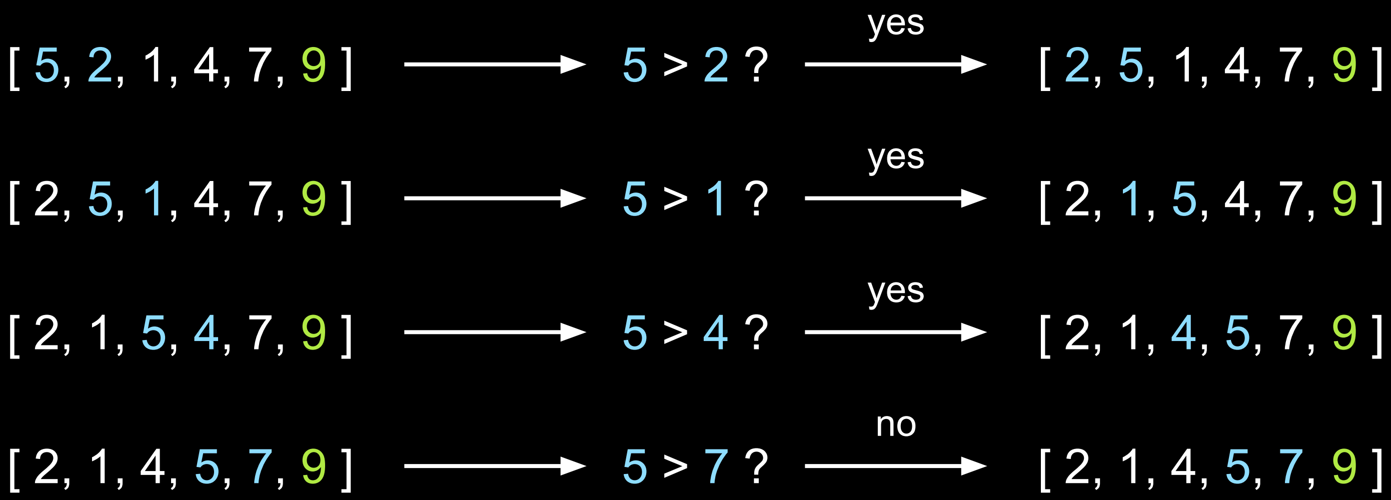
$$[\,5, 2, 1, 4, 7, 9\,] \longrightarrow 5 > 2\ ? \xrightarrow{\text{yes}} [\,2, 5, 1, 4, 7, 9\,]$$

$$[\,2, 5, 1, 4, 7, 9\,] \longrightarrow 5 > 1\ ? \xrightarrow{\text{yes}} [\,2, 1, 5, 4, 7, 9\,]$$

$[\,5, 2, 1, 4, 7, 9\,] \longrightarrow 5 > 2\ ? \xrightarrow{\text{yes}} [\,2, 5, 1, 4, 7, 9\,]$

$[\,2, 5, 1, 4, 7, 9\,] \longrightarrow 5 > 1\ ? \xrightarrow{\text{yes}} [\,2, 1, 5, 4, 7, 9\,]$

$[\,2, 1, 5, 4, 7, 9\,] \longrightarrow 5 > 4\ ? \xrightarrow{\text{yes}} [\,2, 1, 4, 5, 7, 9\,]$



[5, 2, 1, 4, 7, 9] → 5 > 2 ? $\xrightarrow{\text{yes}}$ [2, 5, 1, 4, 7, 9]

[2, 5, 1, 4, 7, 9] → 5 > 1 ? $\xrightarrow{\text{yes}}$ [2, 1, 5, 4, 7, 9]

[2, 1, 5, 4, 7, 9] → 5 > 4 ? $\xrightarrow{\text{yes}}$ [2, 1, 4, 5, 7, 9]

[2, 1, 4, 5, 7, 9] → 5 > 7 ? $\xrightarrow{\text{no}}$ [2, 1, 4, 5, 7, 9]

$$[\ 2,\ 1,\ 4,\ 5,\ 7,\ 9\ ] \longrightarrow 2 > 1\ ? \xrightarrow{\text{yes}} [\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ]$$

$$[\ 2, 1, 4, 5, 7, 9\ ] \longrightarrow 2 > 1\ ? \xrightarrow{\text{yes}} [\ 1, 2, 4, 5, 7, 9\ ]$$

$$[\ 1, 2, 4, 5, 7, 9\ ] \longrightarrow 2 > 4\ ? \xrightarrow{\text{no}} [\ 1, 2, 4, 5, 7, 9\ ]$$

$$[\,2, 1, 4, 5, 7, 9\,] \longrightarrow 2 > 1\ ? \xrightarrow{\text{yes}} [\,1, 2, 4, 5, 7, 9\,]$$

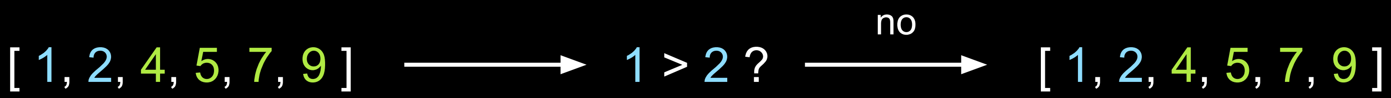
$$[\,1, 2, 4, 5, 7, 9\,] \longrightarrow 2 > 4\ ? \xrightarrow{\text{no}} [\,1, 2, 4, 5, 7, 9\,]$$

$$[\,1, 2, 4, 5, 7, 9\,] \longrightarrow 4 > 5\ ? \xrightarrow{\text{no}} [\,1, 2, 4, 5, 7, 9\,]$$

$$[\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ] \longrightarrow 1 > 2\ ? \xrightarrow{\text{no}} [\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ]$$

$$[\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ] \longrightarrow 1 > 2\ ? \xrightarrow{\text{no}} [\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ]$$

$$[\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ] \longrightarrow 2 > 4\ ? \xrightarrow{\text{no}} [\ 1,\ 2,\ 4,\ 5,\ 7,\ 9\ ]$$



[1, 2, 4, 5, 7, 9]

1 > 2 ?

no

[1, 2, 4, 5, 7, 9]

$$[\,1, 2, 4, 5, 7, 9\,] \longrightarrow 1 > 2\ ? \xrightarrow{\text{no}} [\,1, 2, 4, 5, 7, 9\,]$$

[1, 2, 4, 5, 7, 9]   DONE!

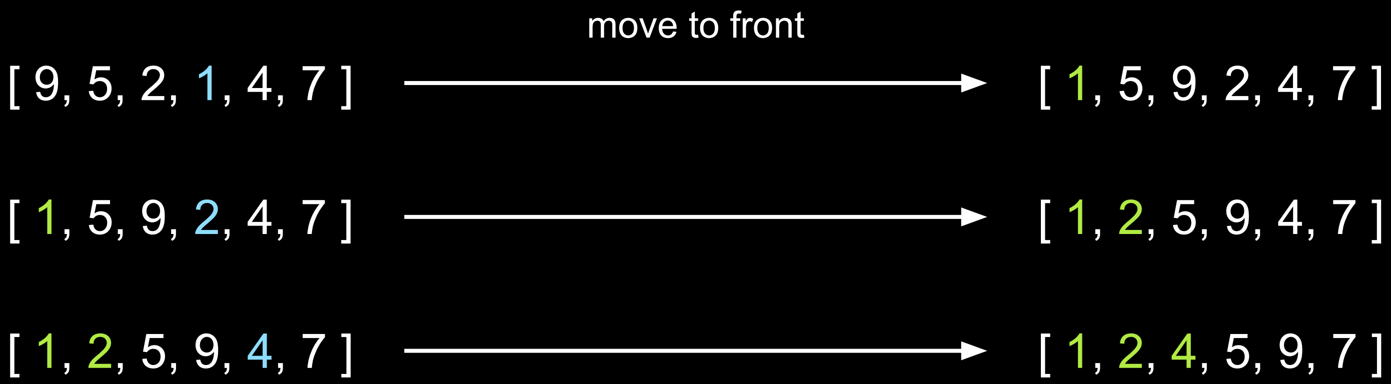
selection sort

find the smallest element and move it to front. repeat for the rest of the elements.

$$[\ 9, 5, 2, 1, 4, 7\ ] \xrightarrow{\text{move to front}} [\ 1, 5, 9, 2, 4, 7\ ]$$

$$[\ 9,\ 5,\ 2,\ 1,\ 4,\ 7\ ] \xrightarrow{\text{move to front}} [\ 1,\ 5,\ 9,\ 2,\ 4,\ 7\ ]$$

$$[\ 1,\ 5,\ 9,\ 2,\ 4,\ 7\ ] \longrightarrow [\ 1,\ 2,\ 5,\ 9,\ 4,\ 7\ ]$$

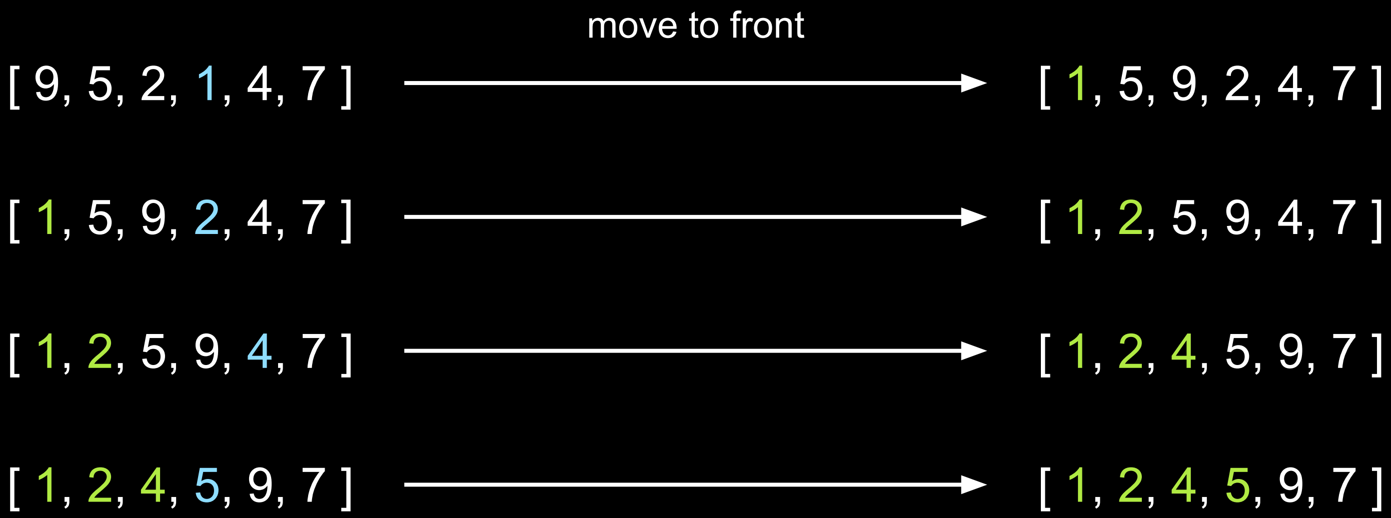


move to front

[9, 5, 2, 1, 4, 7] → [1, 5, 9, 2, 4, 7]

[1, 5, 9, 2, 4, 7] → [1, 2, 5, 9, 4, 7]

[1, 2, 5, 9, 4, 7] → [1, 2, 4, 5, 9, 7]



move to front

[9, 5, 2, 1, 4, 7] → [1, 5, 9, 2, 4, 7]

[1, 5, 9, 2, 4, 7] → [1, 2, 5, 9, 4, 7]

[1, 2, 5, 9, 4, 7] → [1, 2, 4, 5, 9, 7]

[1, 2, 4, 5, 9, 7] → [1, 2, 4, 5, 9, 7]

move to front

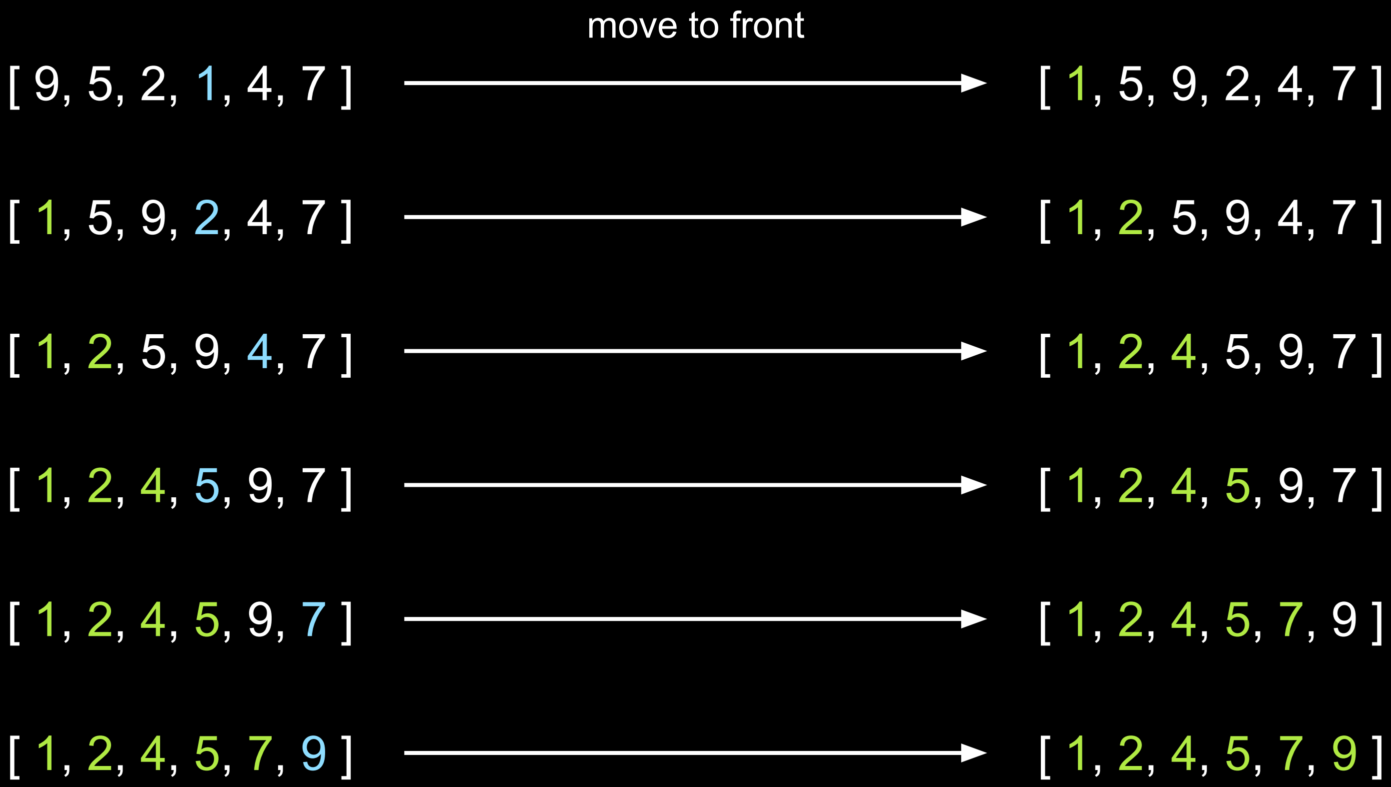
[9, 5, 2, 1, 4, 7] → [1, 5, 9, 2, 4, 7]

[1, 5, 9, 2, 4, 7] → [1, 2, 5, 9, 4, 7]

[1, 2, 5, 9, 4, 7] → [1, 2, 4, 5, 9, 7]

[1, 2, 4, 5, 9, 7] → [1, 2, 4, 5, 9, 7]

[1, 2, 4, 5, 9, 7] → [1, 2, 4, 5, 7, 9]



move to front

[9, 5, 2, 1, 4, 7] → [1, 5, 9, 2, 4, 7]

[1, 5, 9, 2, 4, 7] → [1, 2, 5, 9, 4, 7]

[1, 2, 5, 9, 4, 7] → [1, 2, 4, 5, 9, 7]

[1, 2, 4, 5, 9, 7] → [1, 2, 4, 5, 9, 7]

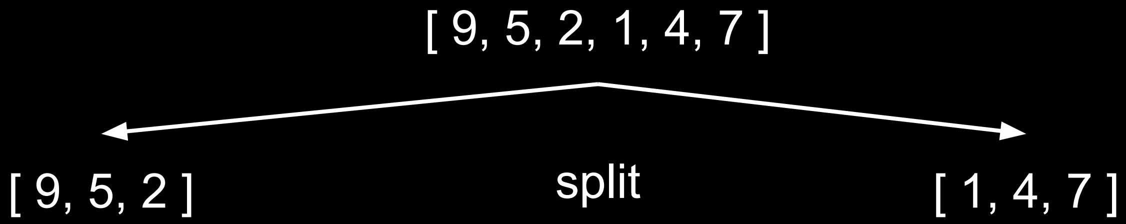
[1, 2, 4, 5, 9, 7] → [1, 2, 4, 5, 7, 9]

[1, 2, 4, 5, 7, 9] → [1, 2, 4, 5, 7, 9]

merge sort

divide the elements recursively in two
halves until only one element is left.
then merge the sorted halves back together.

divide the elements recursively in two halves until only one element is left.
then merge the sorted halves back together.

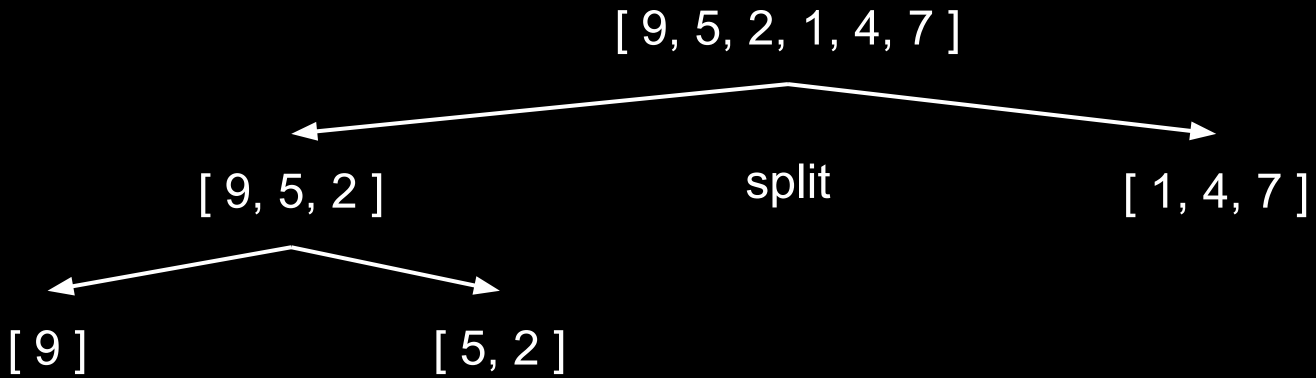


[9, 5, 2, 1, 4, 7]

[9, 5, 2]

split

[1, 4, 7]



[9, 5, 2, 1, 4, 7]

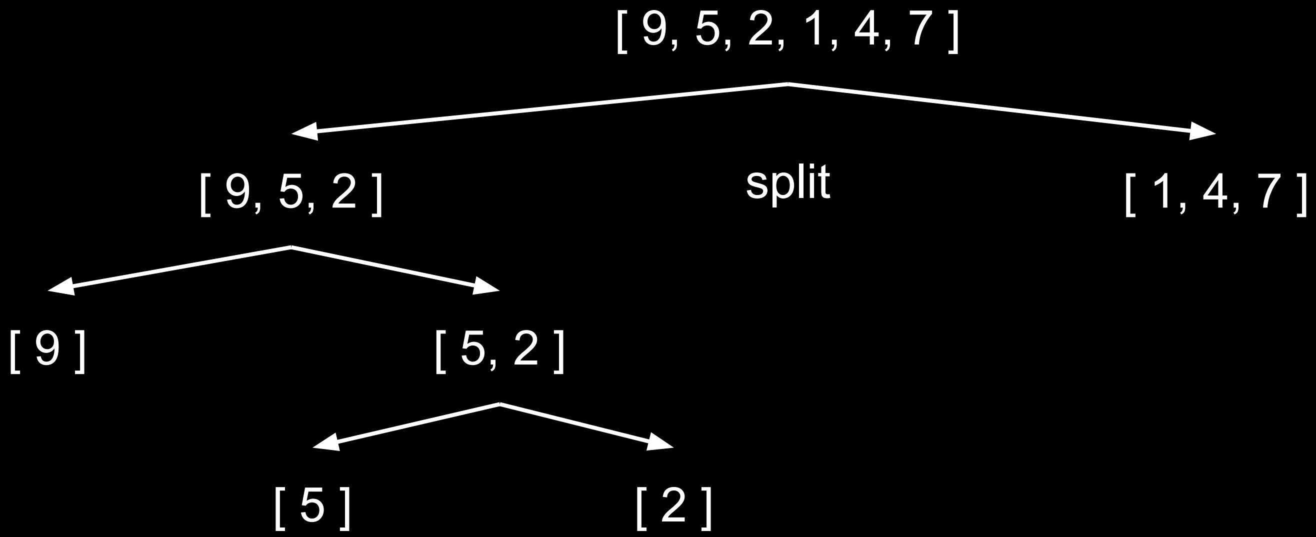
split

[9, 5, 2]

[1, 4, 7]

[9]

[5, 2]



[9, 5, 2, 1, 4, 7]

split

[9, 5, 2]

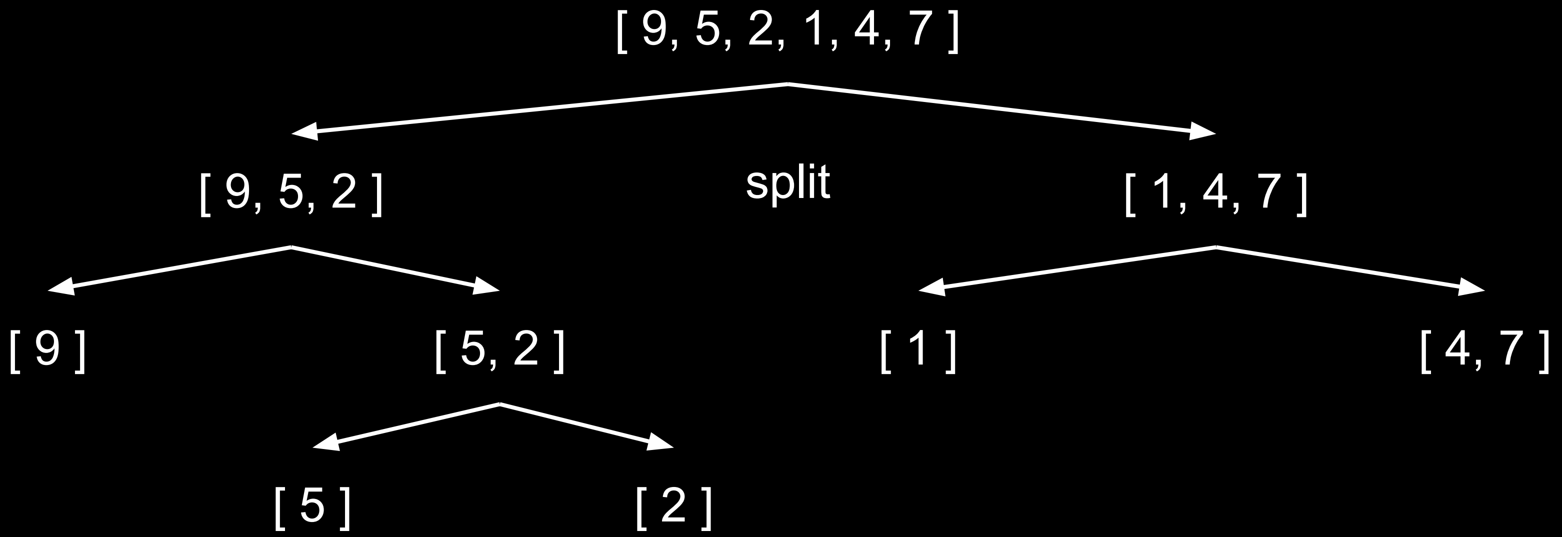
[1, 4, 7]

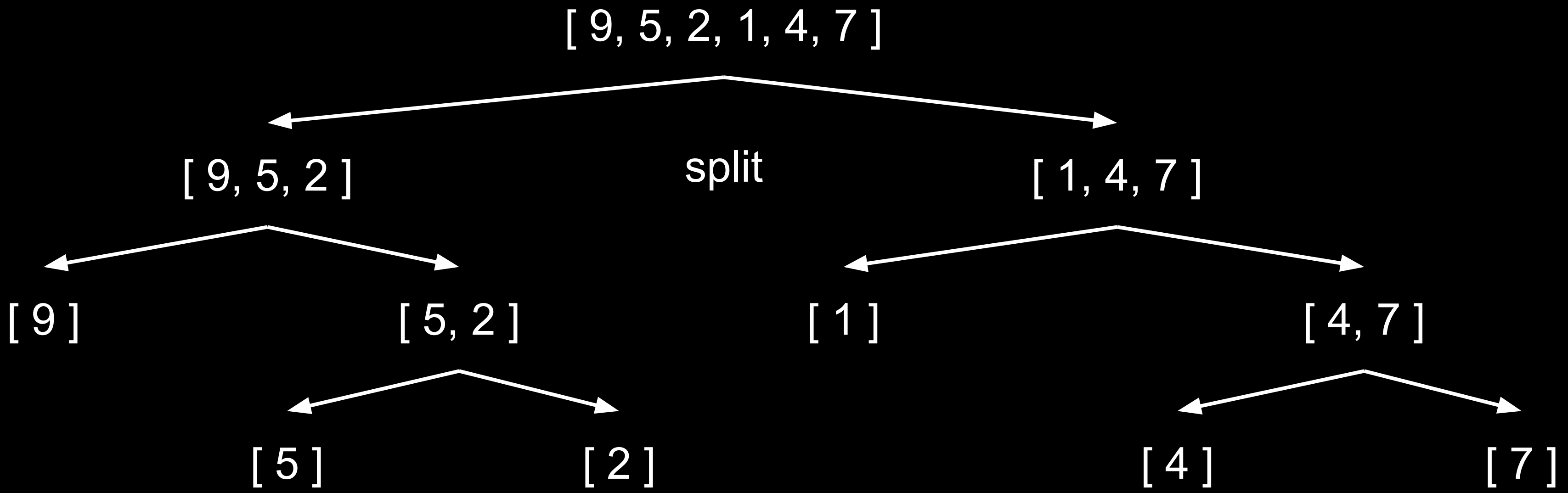
[9]

[5, 2]

[5]

[2]





[9, 5, 2, 1, 4, 7]

split

[9, 5, 2]

[1, 4, 7]

[9]

[5, 2]

[1]

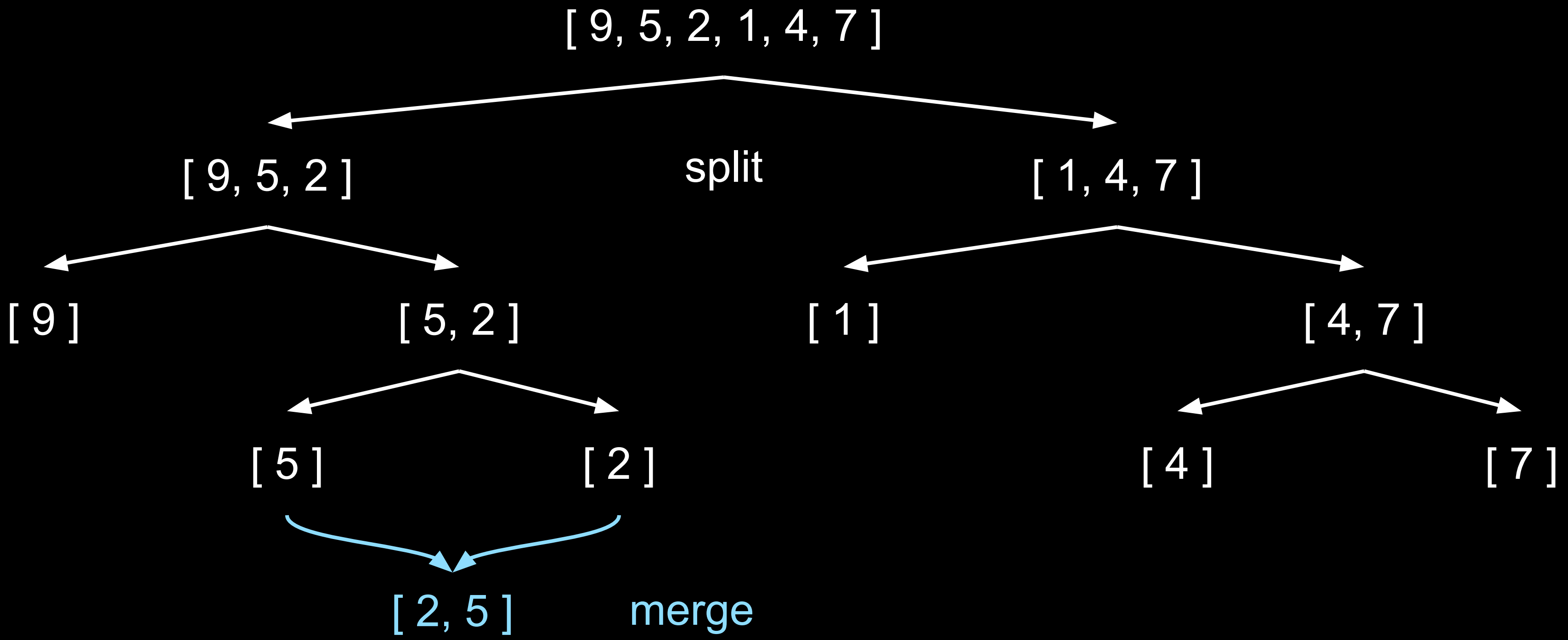
[4, 7]

[5]

[2]

[4]

[7]



[9, 5, 2, 1, 4, 7]

split

[9, 5, 2]

[1, 4, 7]

[9]

[5, 2]

[1]

[4, 7]

[5]

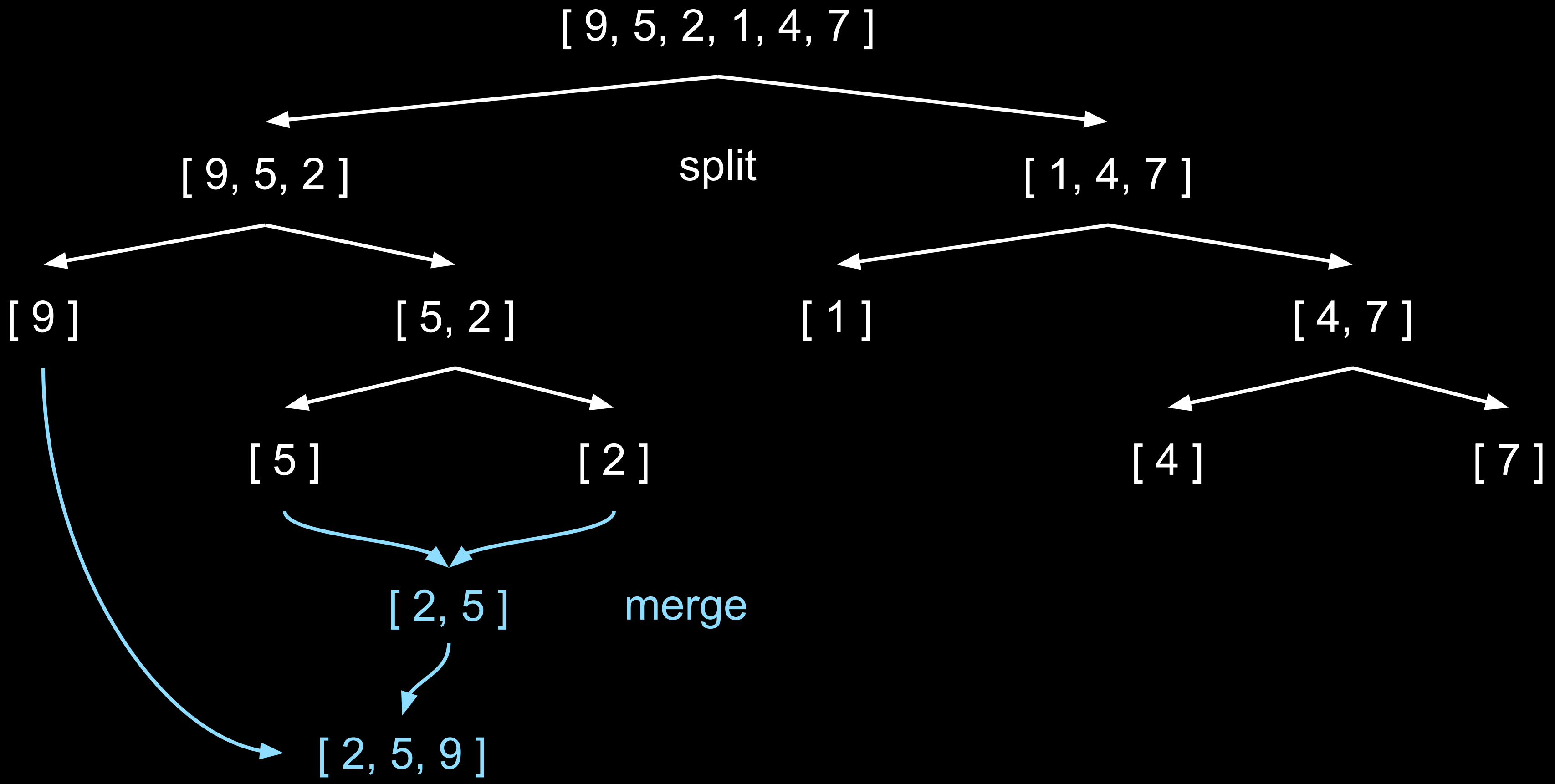
[2]

[4]

[7]

[2, 5]

merge



[9, 5, 2, 1, 4, 7]

split

[9, 5, 2]

[1, 4, 7]

[9]

[5, 2]

[1]

[4, 7]

[5]

[2]

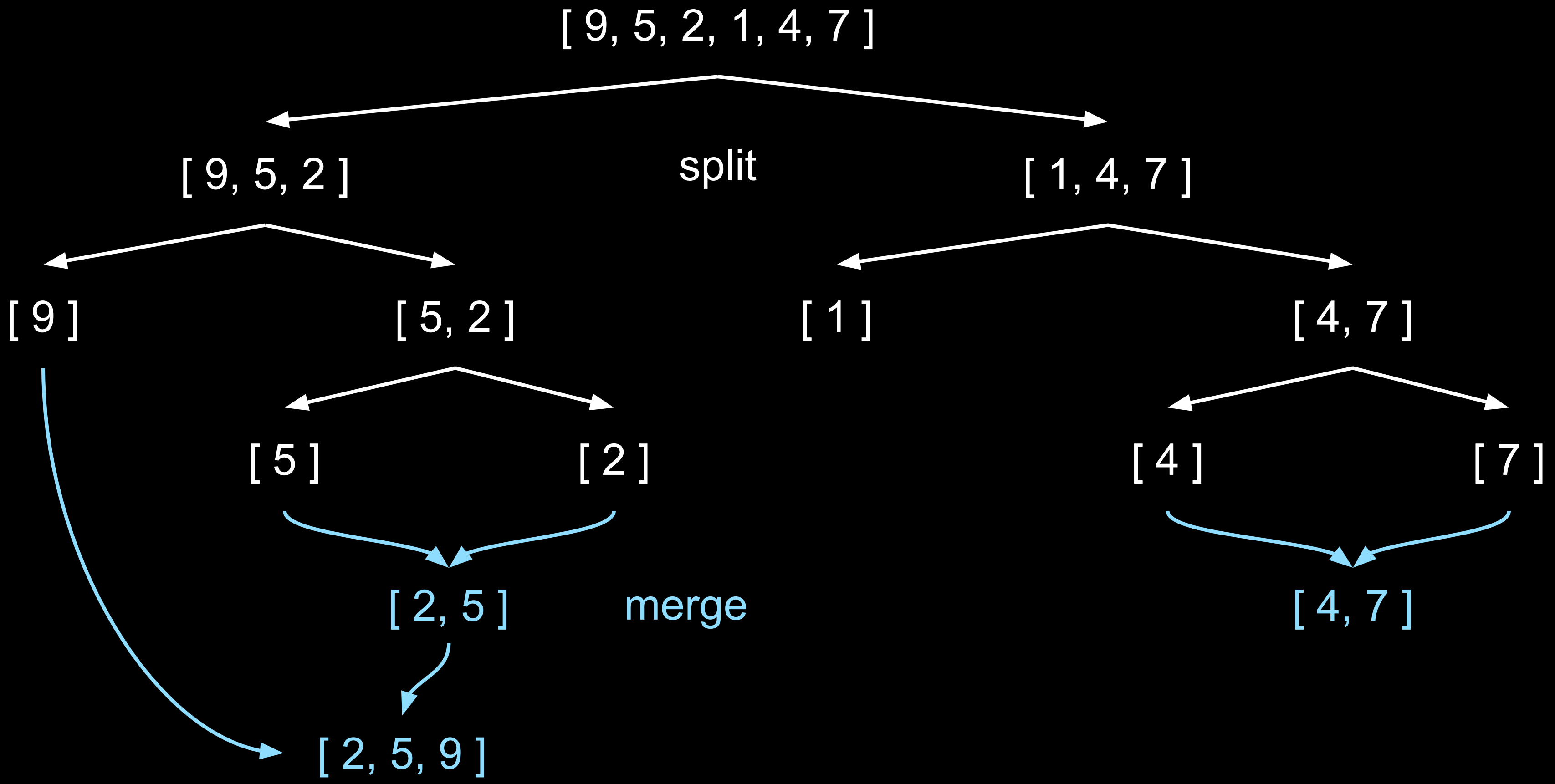
[4]

[7]

[2, 5]

merge

[2, 5, 9]



[9, 5, 2, 1, 4, 7]

[9, 5, 2]

split

[1, 4, 7]

[9]

[5, 2]

[1]

[4, 7]

[5]

[2]

[4]

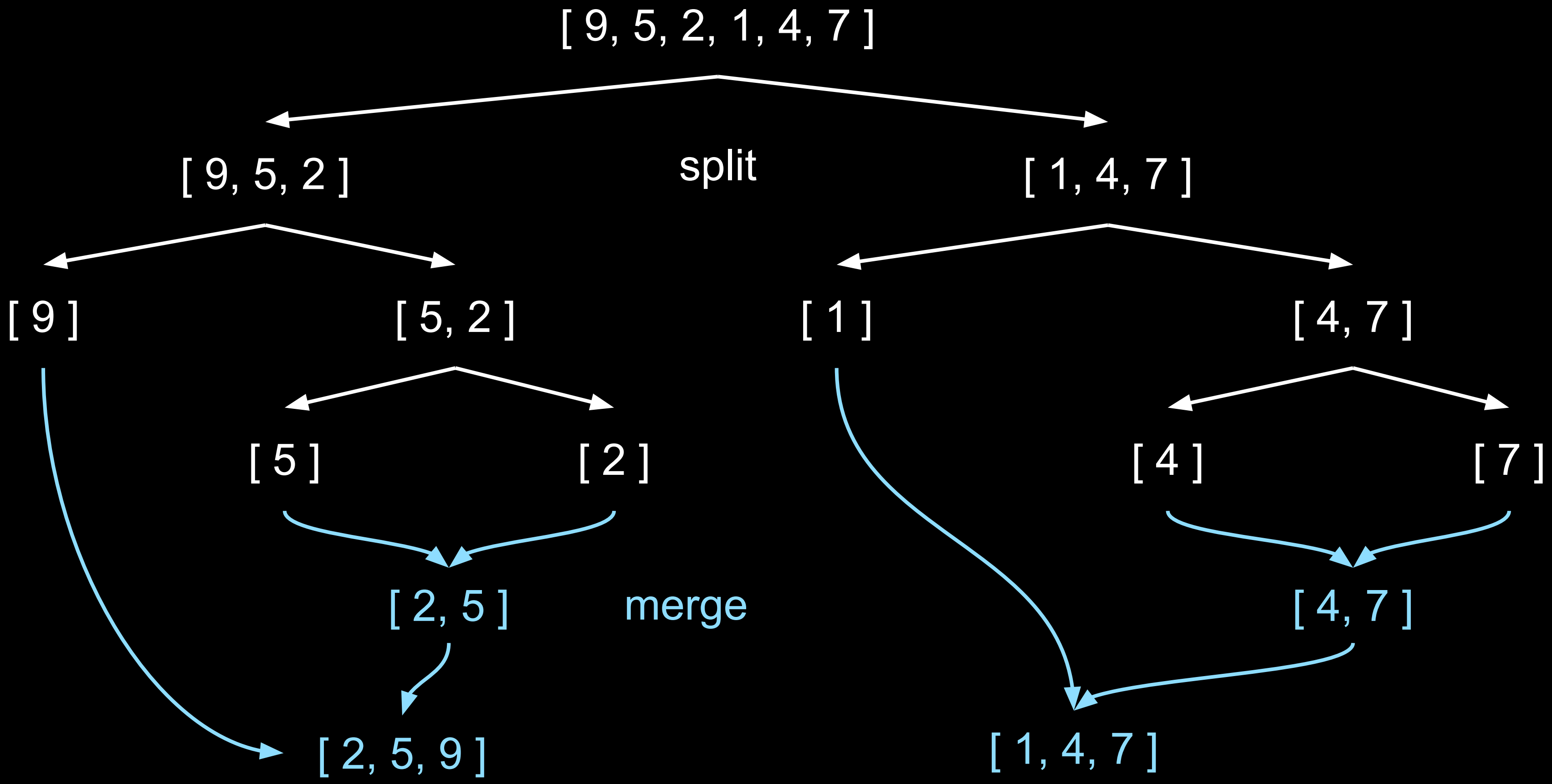
[7]

[2, 5]

merge

[4, 7]

[2, 5, 9]



[9, 5, 2, 1, 4, 7]

[9, 5, 2]

split

[1, 4, 7]

[9]

[5, 2]

[1]

[4, 7]

[5]

[2]

[4]

[7]

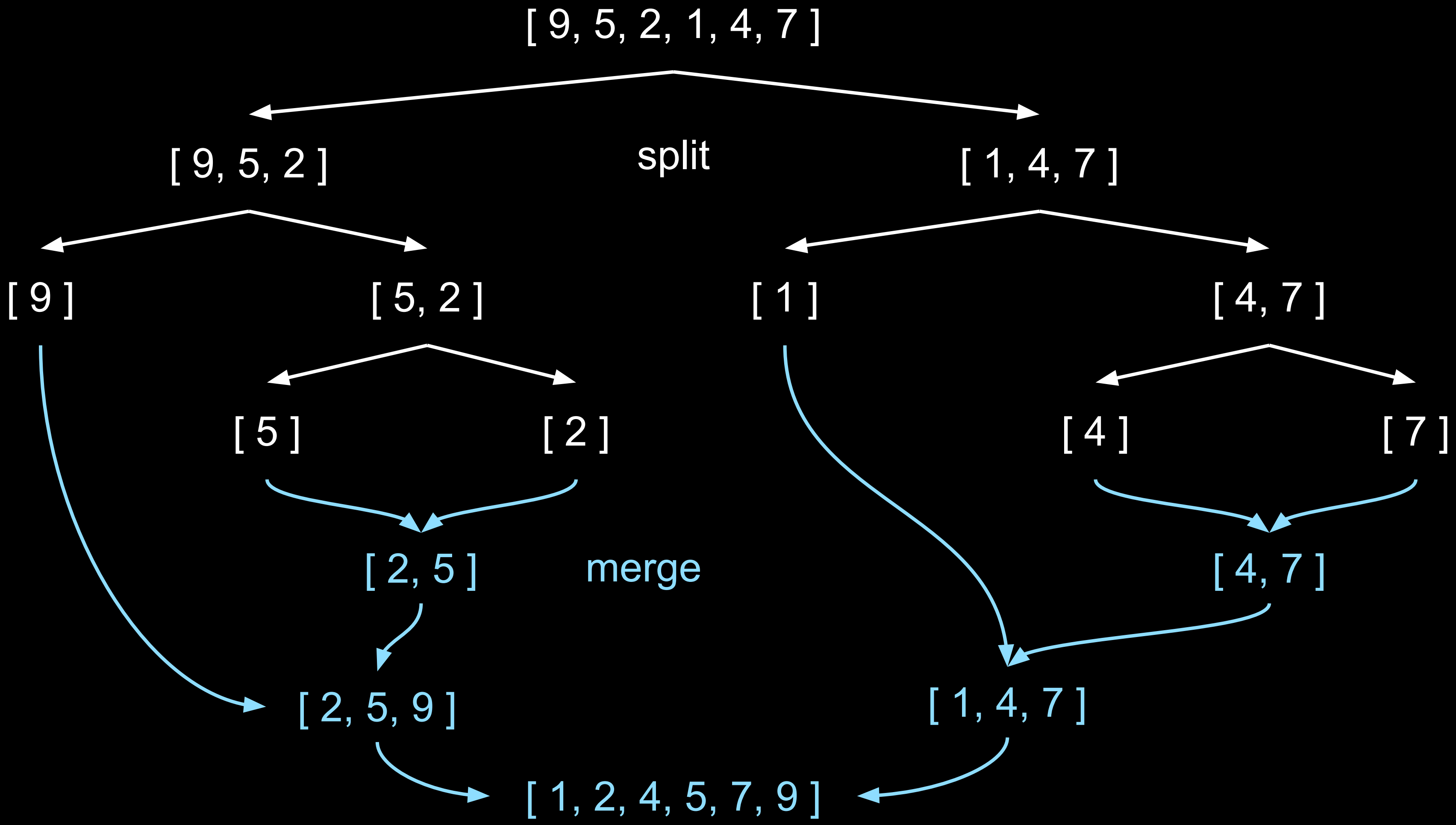
[2, 5]

merge

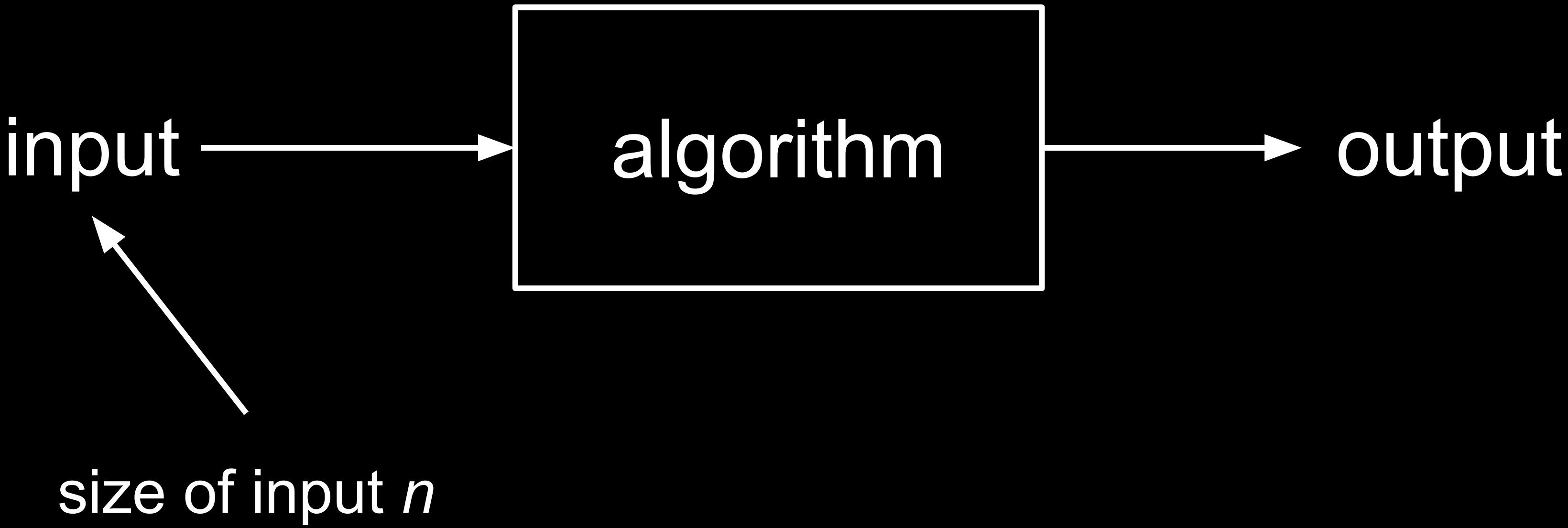
[4, 7]

[2, 5, 9]

[1, 4, 7]


[9, 5, 2, 1, 4, 7]
split
[9, 5, 2]
[1, 4, 7]
[9]
[5, 2]
[1]
[4, 7]
[5]
[2]
[4]
[7]
[2, 5]
merge
[4, 7]
[2, 5, 9]
[1, 4, 7]
[1, 2, 4, 5, 7, 9]

complexity

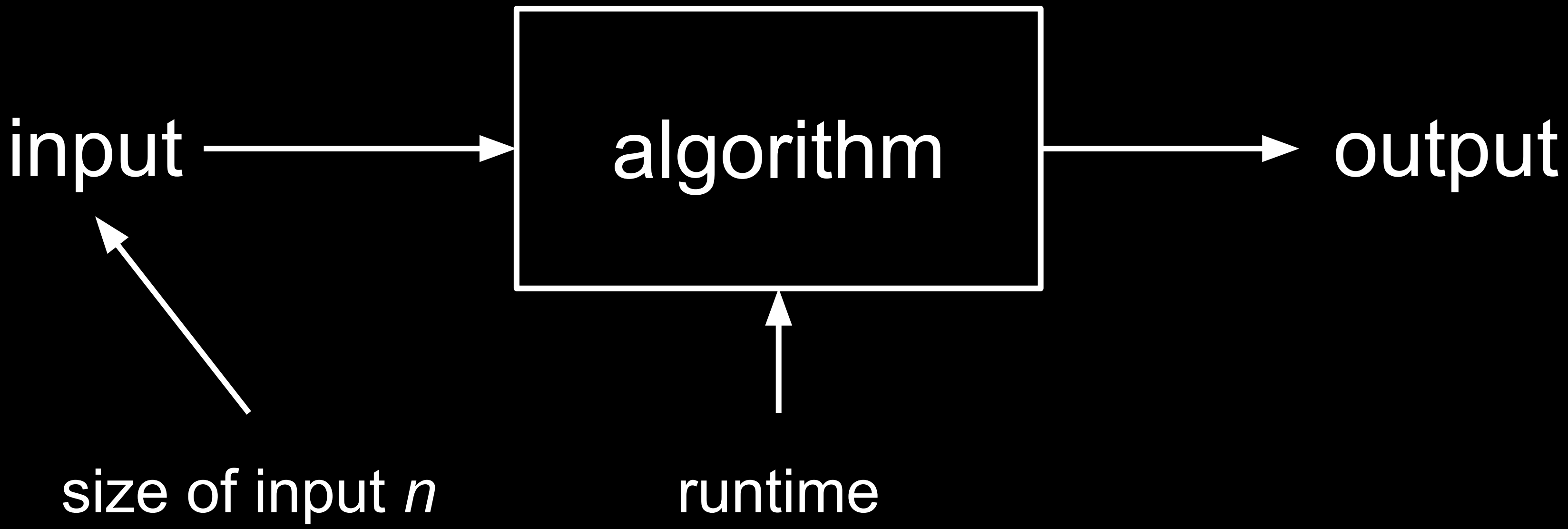


input

algorithm

output

size of input *n*



input

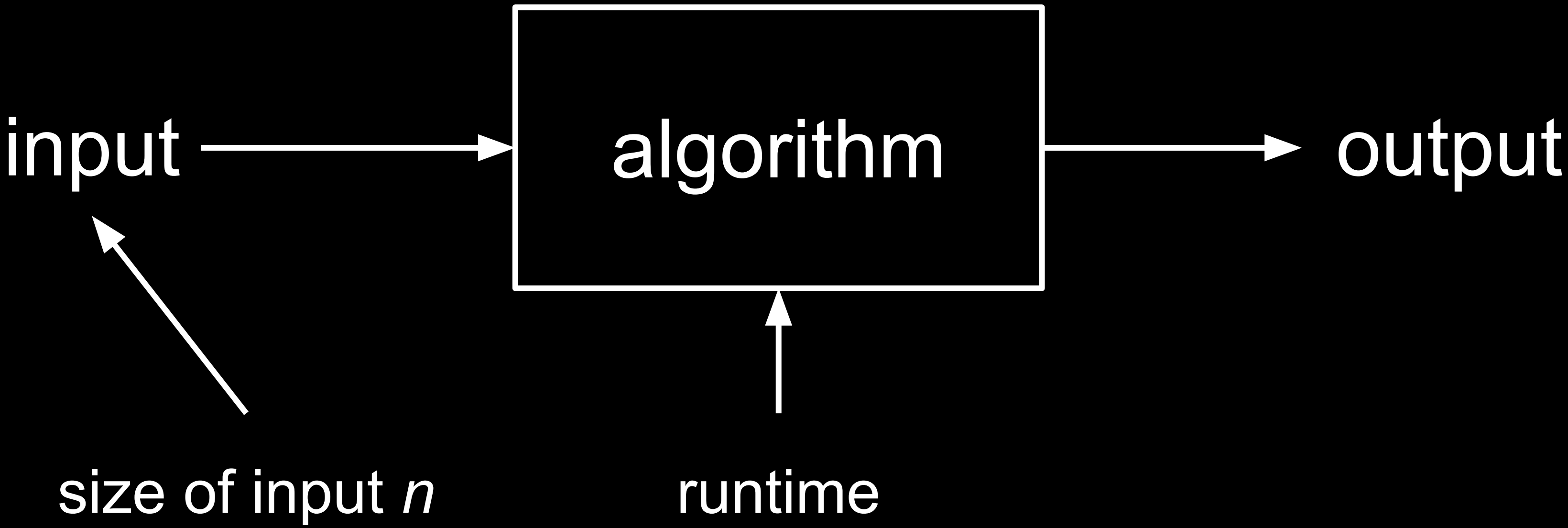
algorithm

output

size of input *n*

runtime

O(n)



input

algorithm

output

size of input *n*

runtime

O(1)	runtime is constant and independent of problem size
$O(\log_2 n)$	runtime is determined by the logarithm of problem size
O(n)	runtime is linear to problem size
$O(n^2)$	runtime grows quadratically with the size of the problem
$O(n^3)$	runtime grows cubically with the size of the problem
$O(2^n)$	runtime grows exponentially with the size of the problem
O(n!)	runtime grows factorially with the size of the problem

input
?
output

optimization

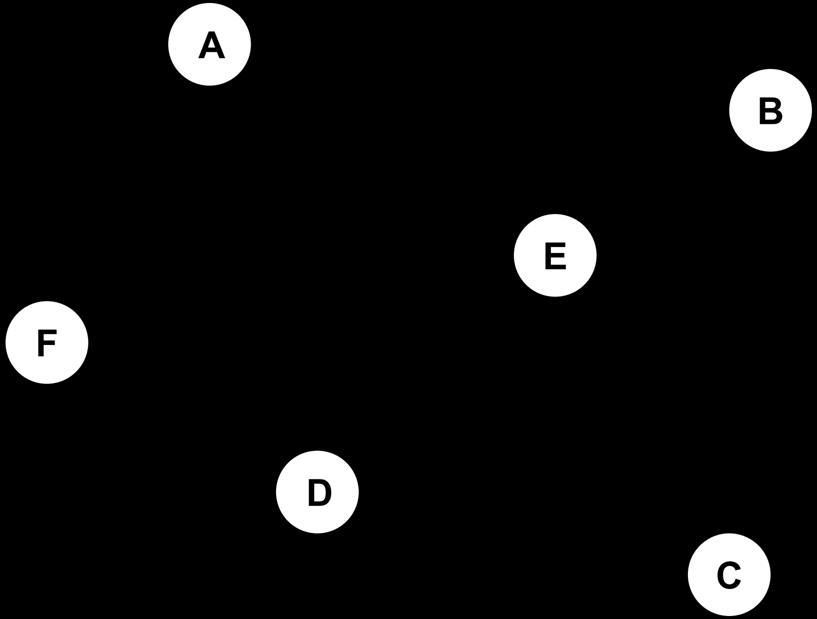
input

?

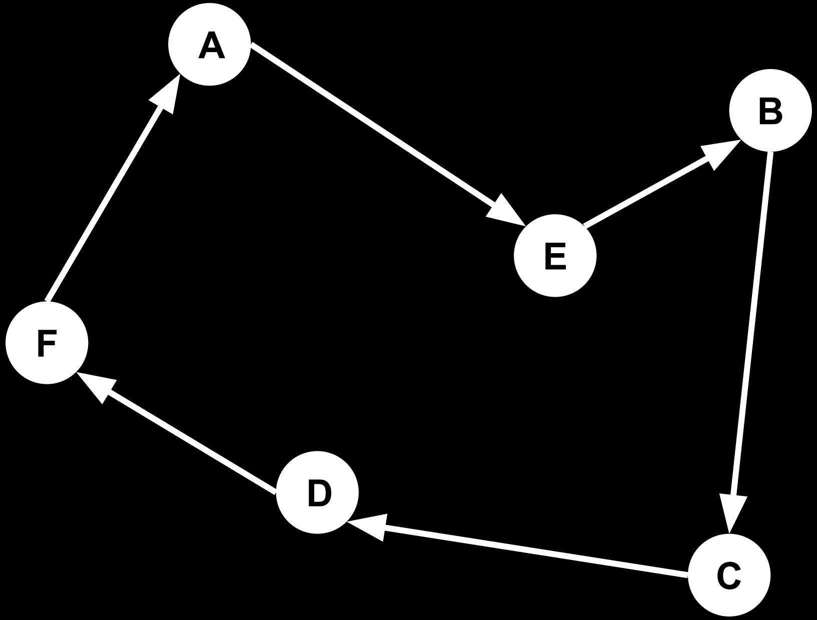
output

traveling salesmen

shortest tour?



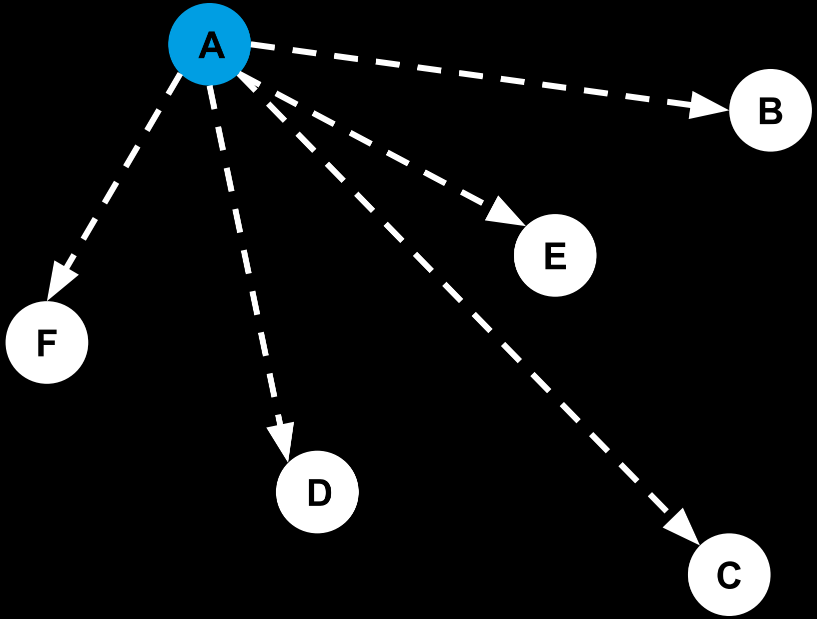
shortest tour?



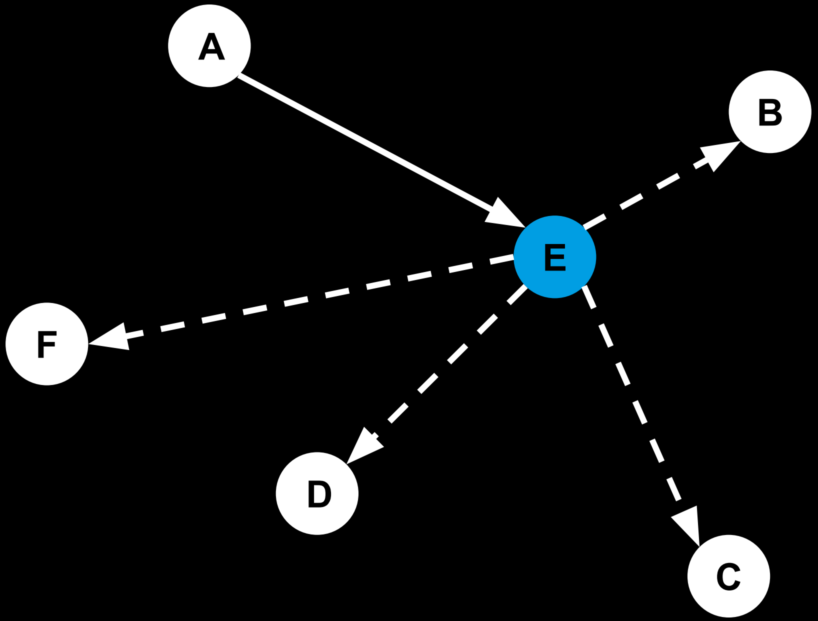
brute force

$$\mathrm{O}(n) = n!$$

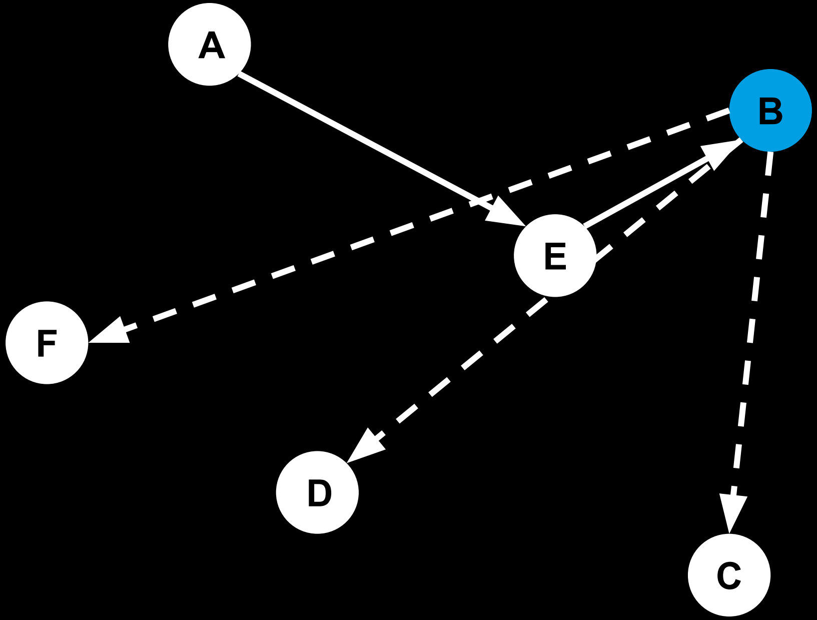
5 possible cities



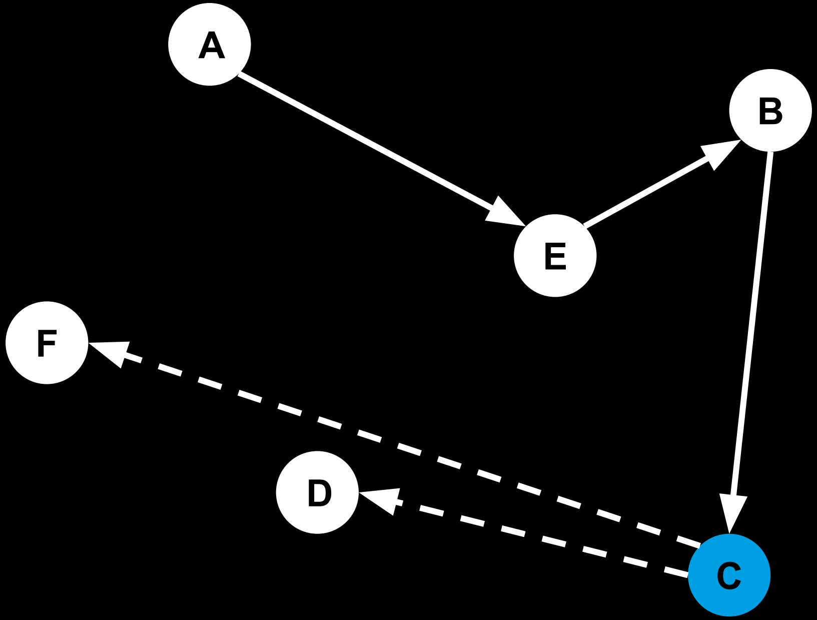
~~5~~ 4 possible cities



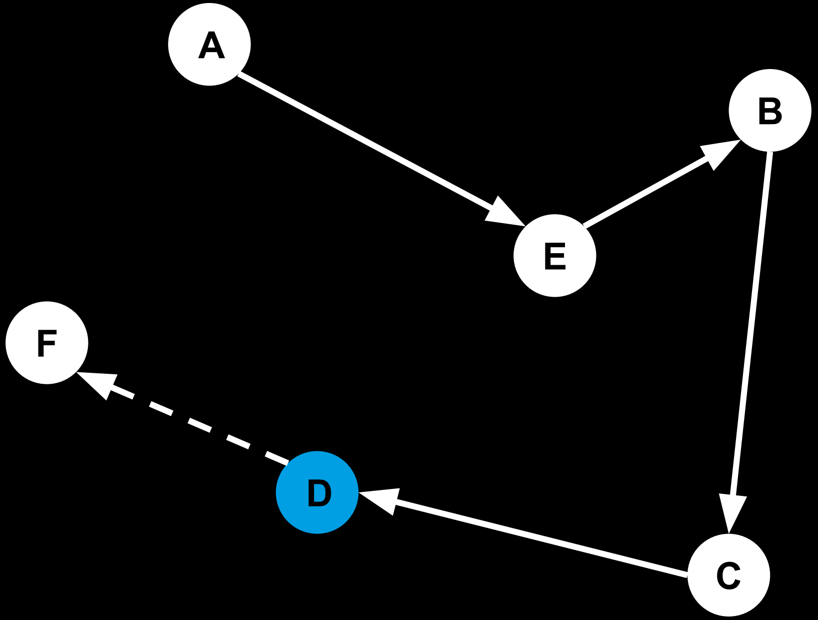
~~5~~ ~~4~~ 3 possible cities



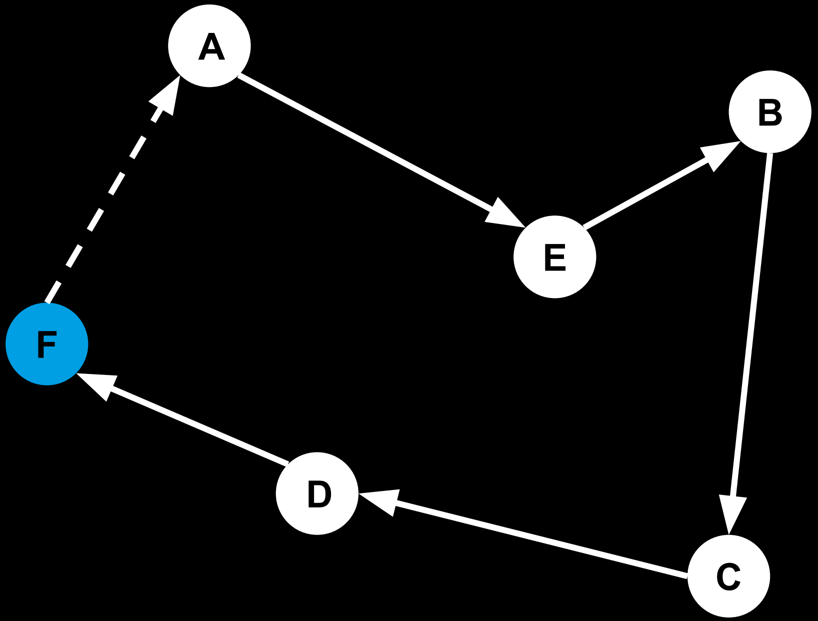
~~5~~ ~~4~~ ~~3~~ 2 possible cities



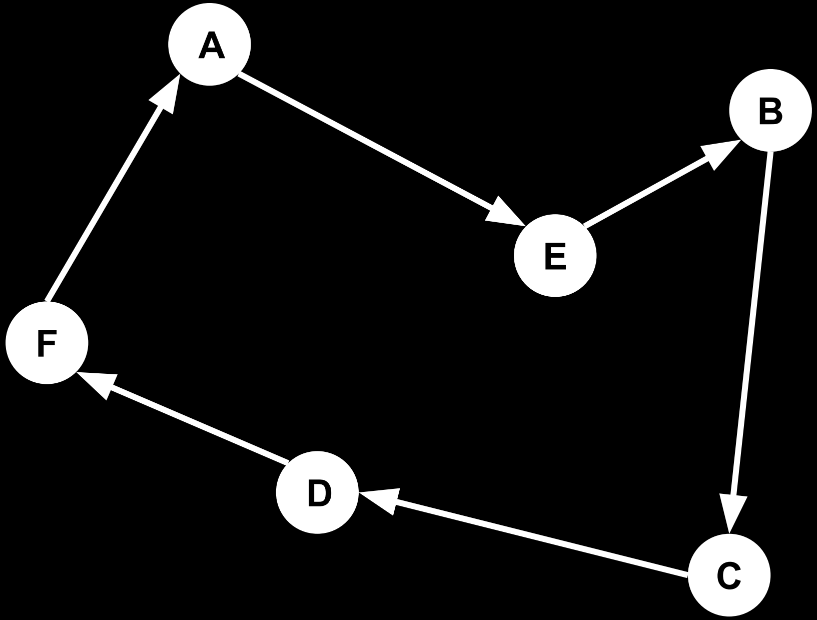
~~5~~ ~~4~~ ~~3~~ ~~2~~ 1 possible city



~~5~~ ~~4~~ ~~3~~ ~~2~~ ~~1~~ return nome



~~5~~ ~~4~~ ~~3~~ ~~2~~ ~~1~~ return nome



$$\mathrm{O}(n) = n!$$

$$n = 5$$

$$\mathrm{O}(n) = n!$$

$$n = 5$$

$$\mathrm{N} = 5 * 4 * 3 * 2 * 1$$

$$O(n) = n!$$

$$n = 5$$

$$N = 5 * 4 * 3 * 2 * 1$$

$$= 120$$

$n = 10$

$n = 20$

$n = 30$

$n = 25$

brute force takes longer than the universe is old

$n = 60$

more possible routes than atoms in the universe

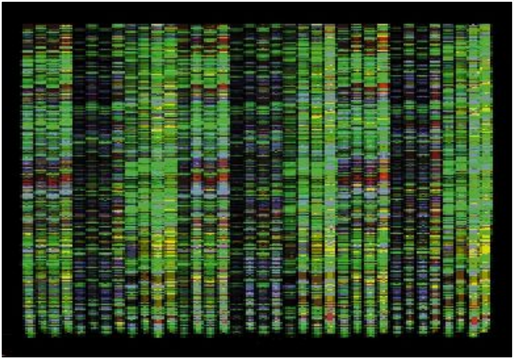


Image source: IEEE

Image source: VDI Nachrichten

Image source: Wikimedia

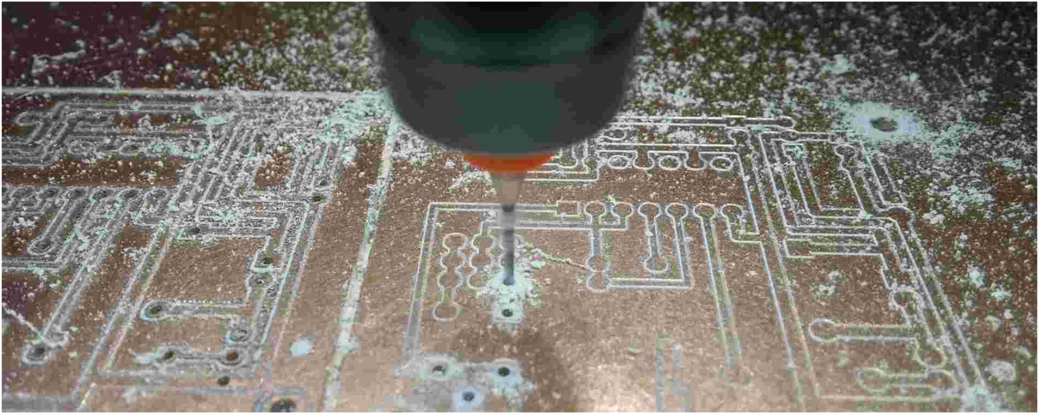
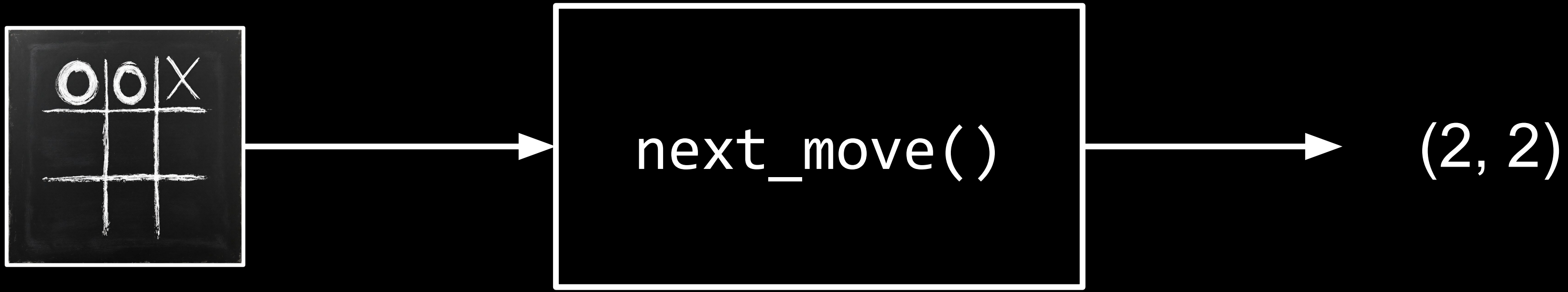


Image source: https://github.com/meiyi1986/tutorials/blob/master/notebooks/img/pcb-drilling.jpeg

Image source: IAS Observatory

but sometimes, brute force works perfectly



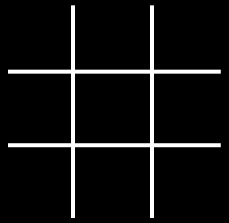
next_move()

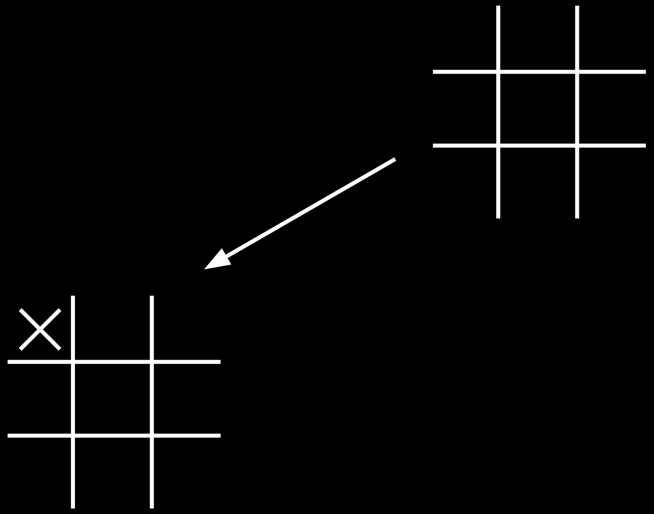
(2, 2)

brute-force search:

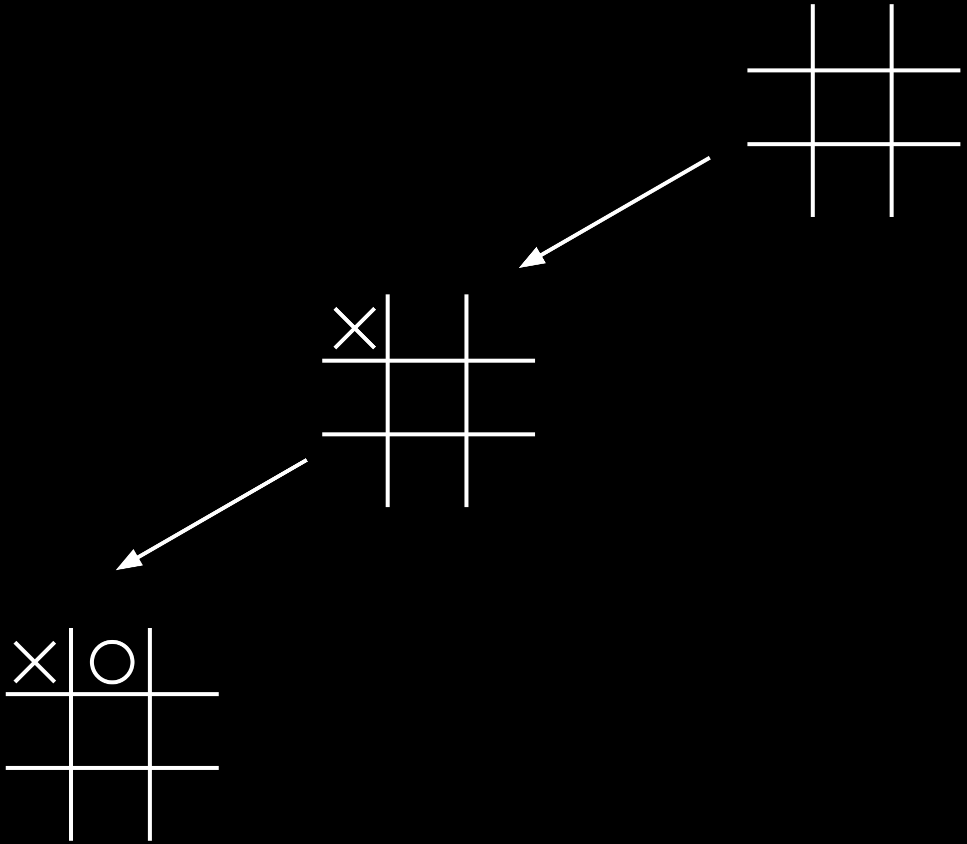
evaluate all possible move sequences.

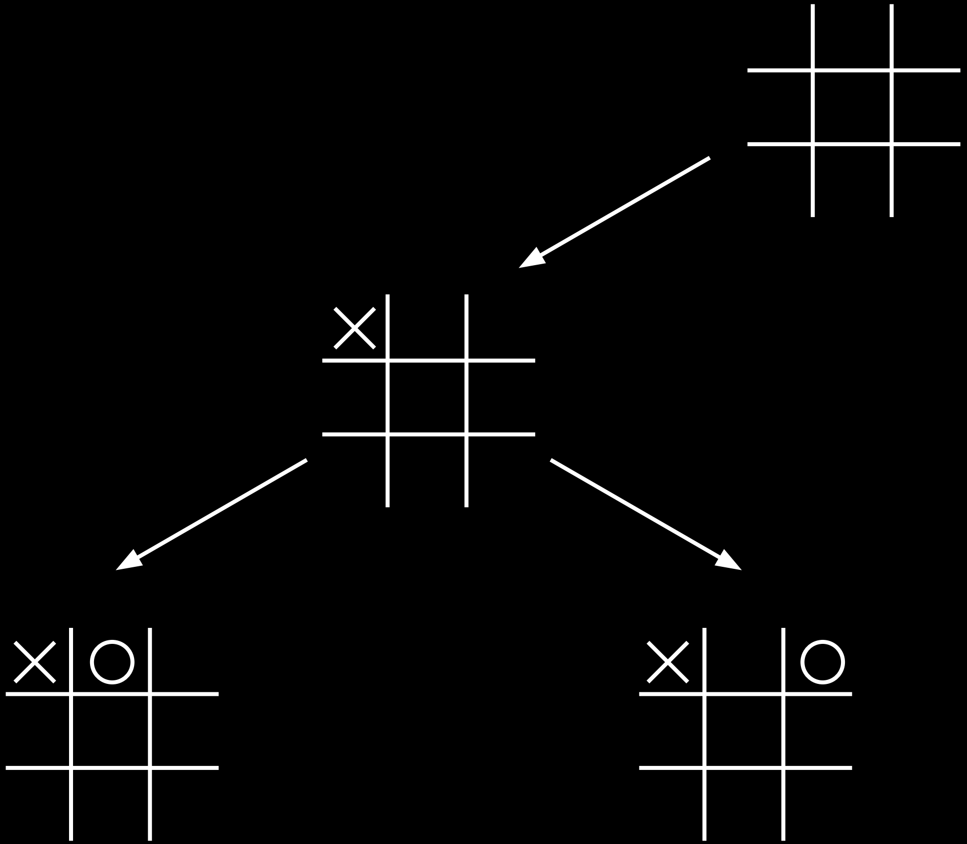
choose the move with the best value.

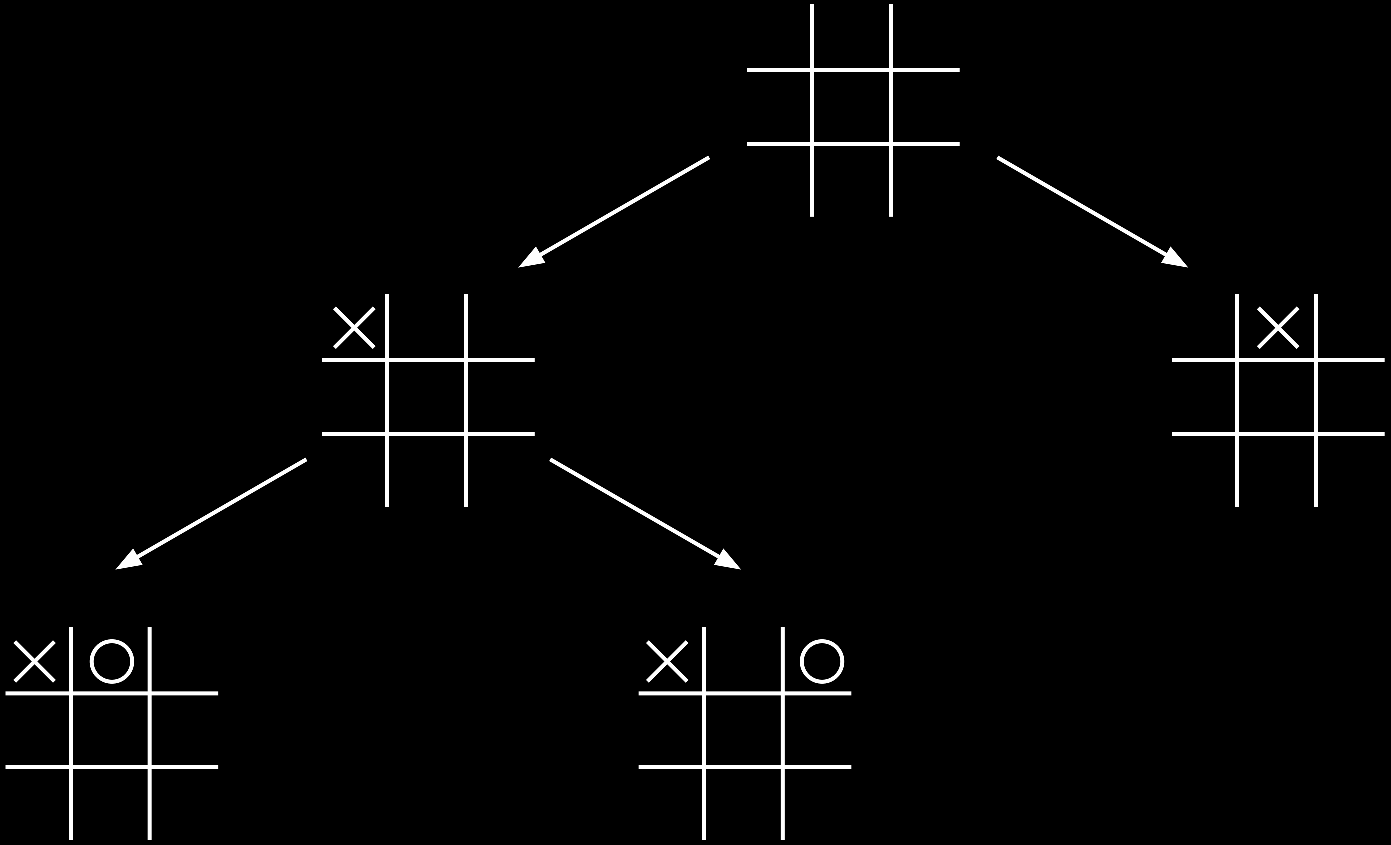


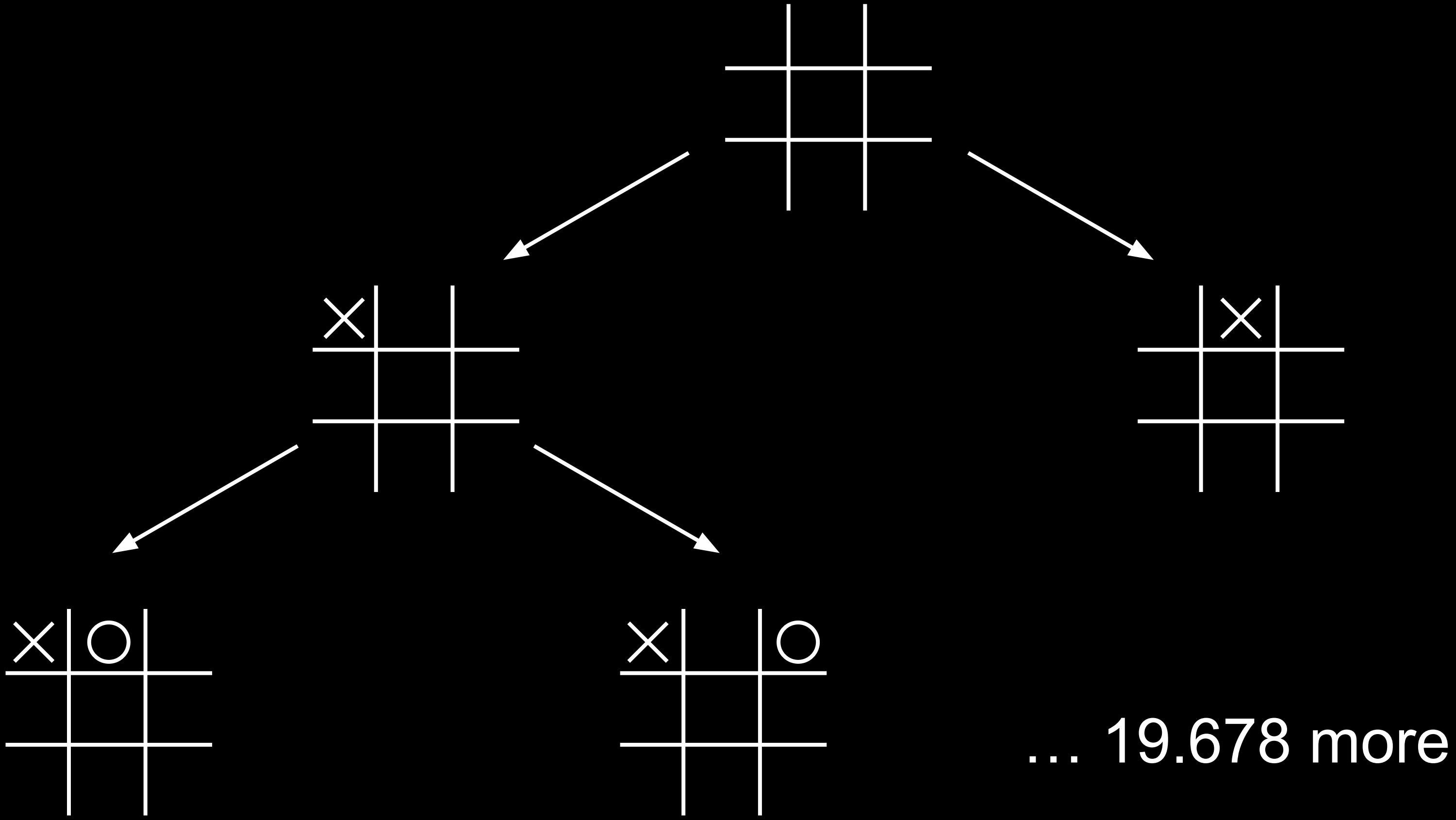


X



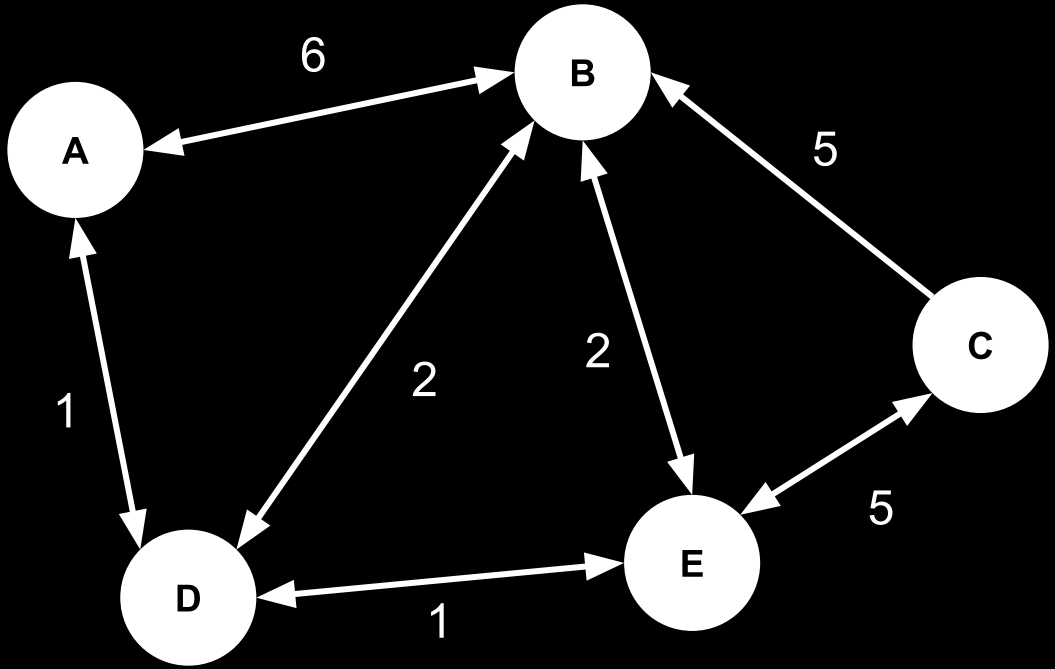



X
X
X O
X O



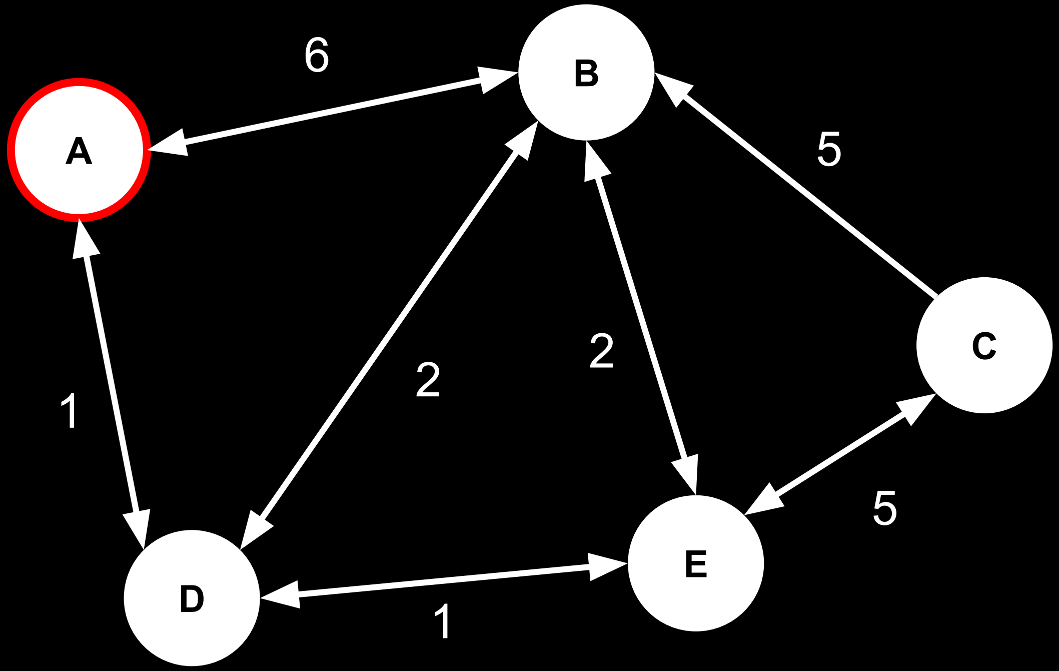
… 19.678 more

shortest paths


A
B
C
D
E
6
5
1
2
2
5
1

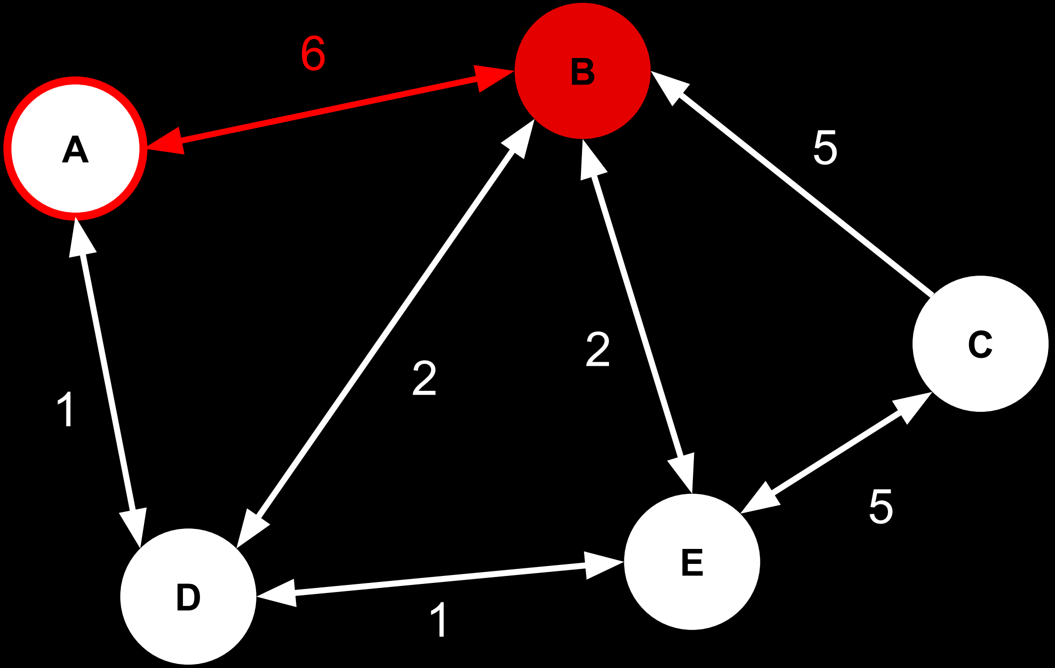
dijkstra's algorithm

Distances: A = 0, B = ∞, C = ∞, D = ∞, E = ∞



Set A as first location

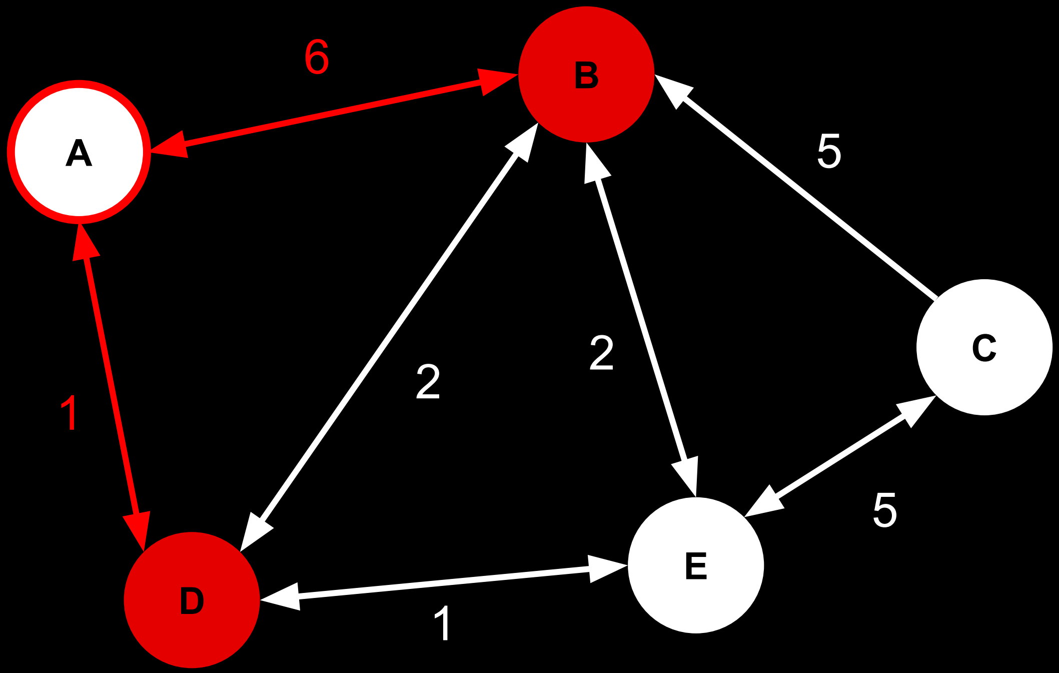
Distances: A = 0, B = 6, C = ∞, D = ∞, E = ∞



Update distance to B to 6

Distances: A = 0, B = 6, C = ∞, D = 1, E = ∞

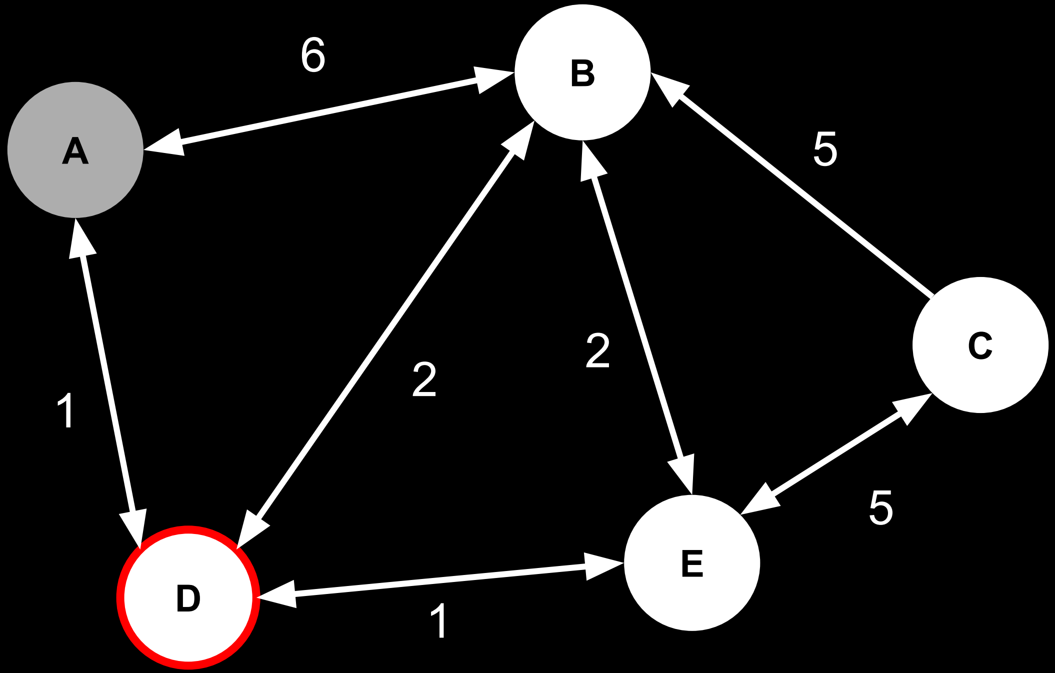
Update distance to D to 1



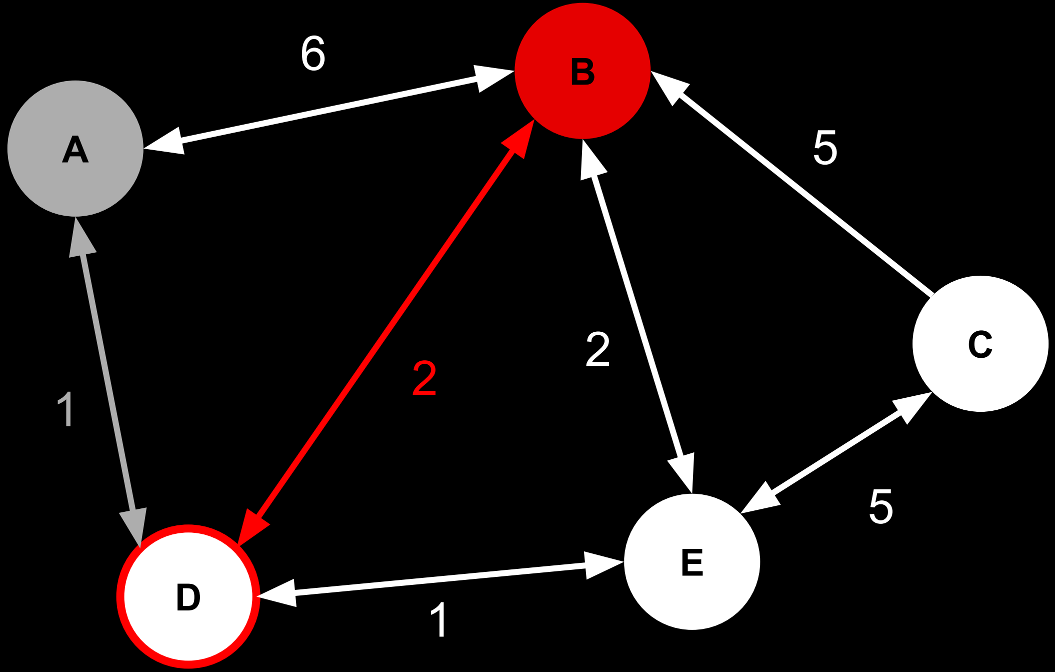
Distances: A = 0, B = 6, C = ∞, D = 1, E = ∞

Move to D as next location

Mark A as visited

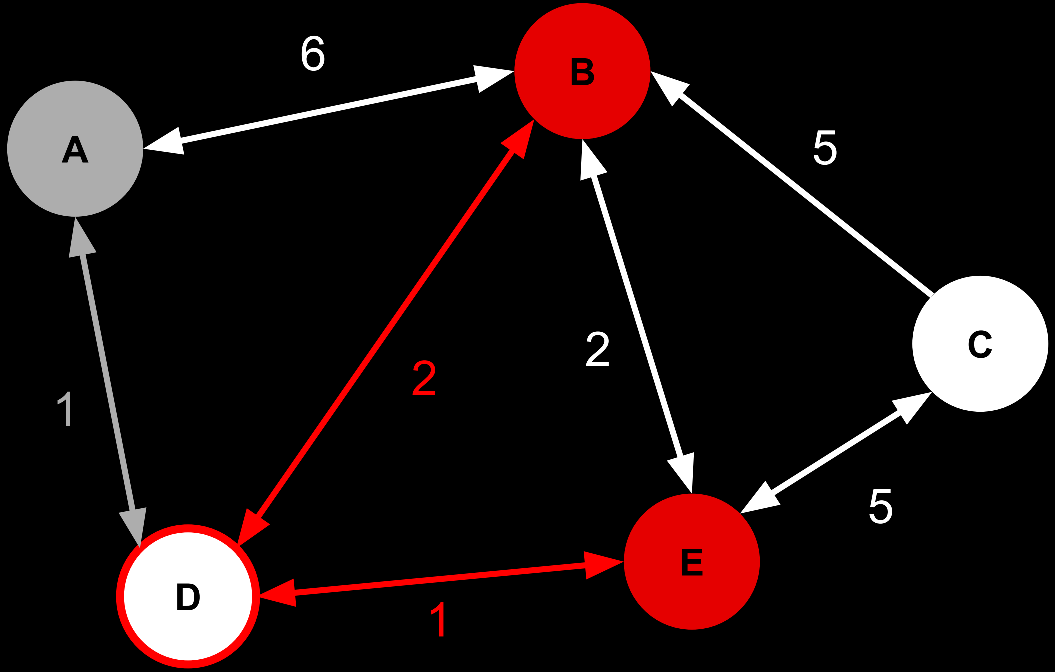


Distances: A = 0, B = 3, C = ∞, D = 1, E = ∞



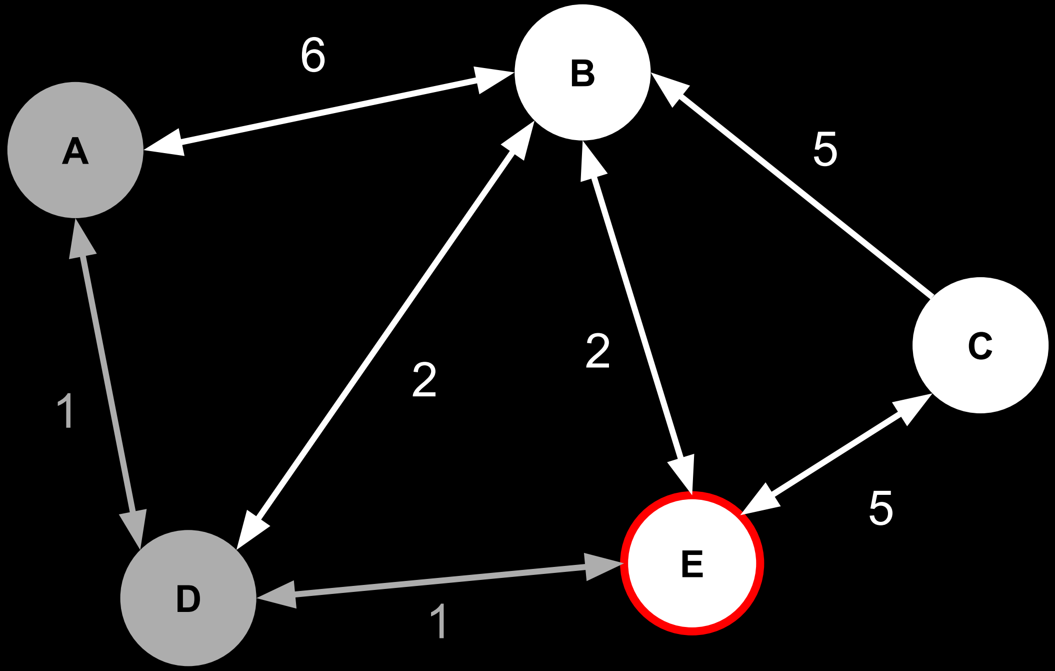
Update distance to B to 3

Distances: A = 0, B = 3, C = ∞, D = 1, E = 2



Update distance
to E to 2

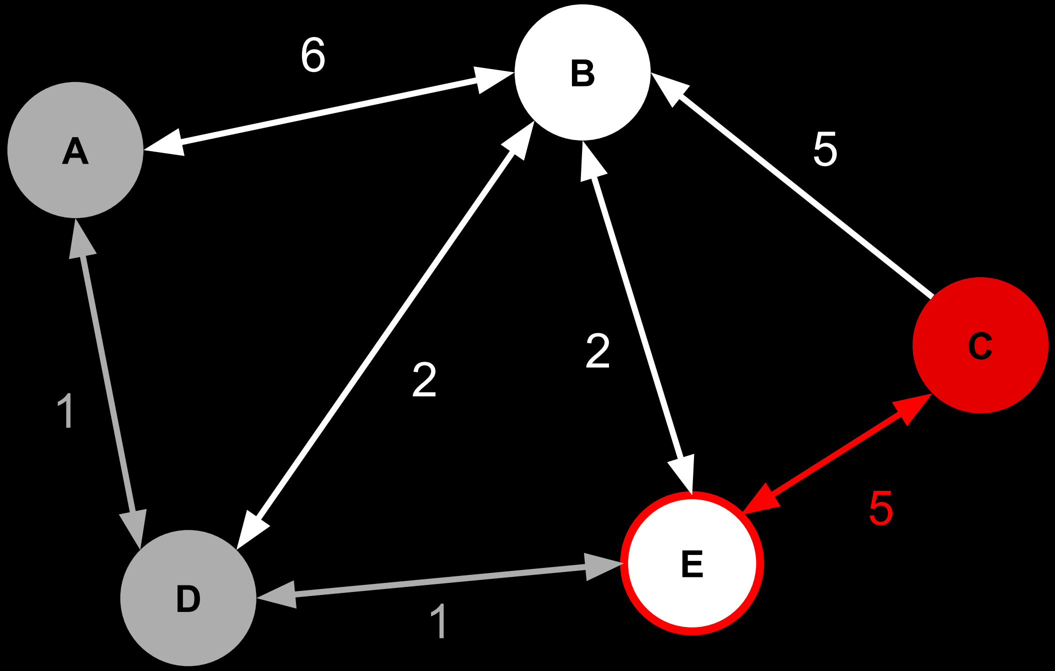
Distances: A = 0, B = 3, C = ∞, D = 1, E = 2



Move to E as next location

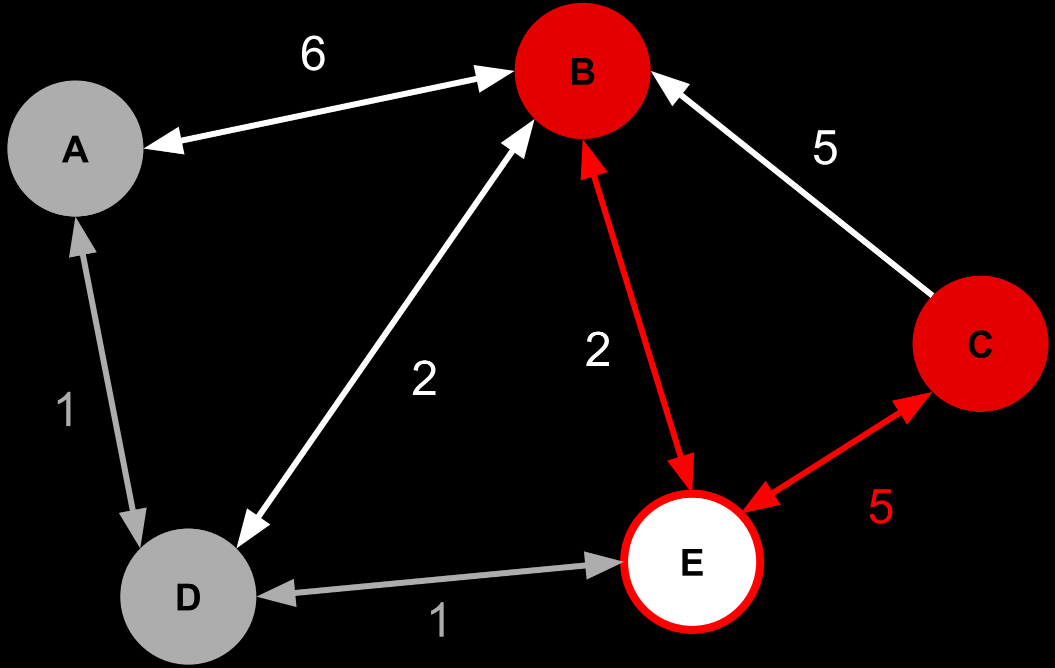
Mark D as visited

Distances: A = 0, B = 3, C = 7, D = 1, E = 2



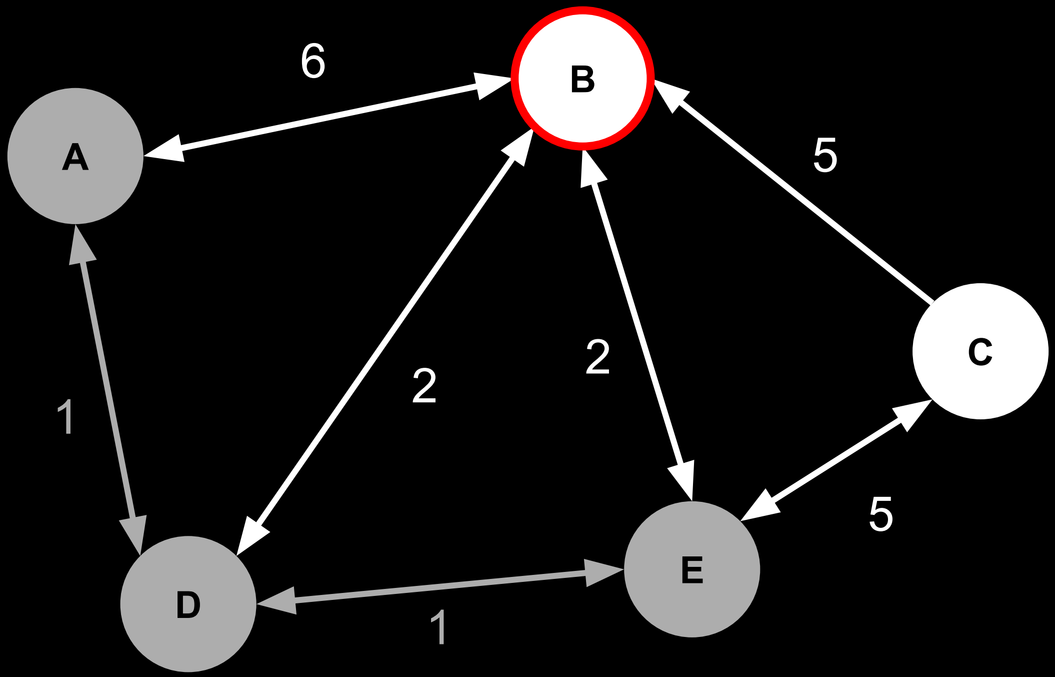
Update distance to C to 7

Distances: A = 0, B = 3, C = 7, D = 1, E = 2



No update for B, shorter path exists

Distances: A = 0, B = 3, C = 7, D = 1, E = 2

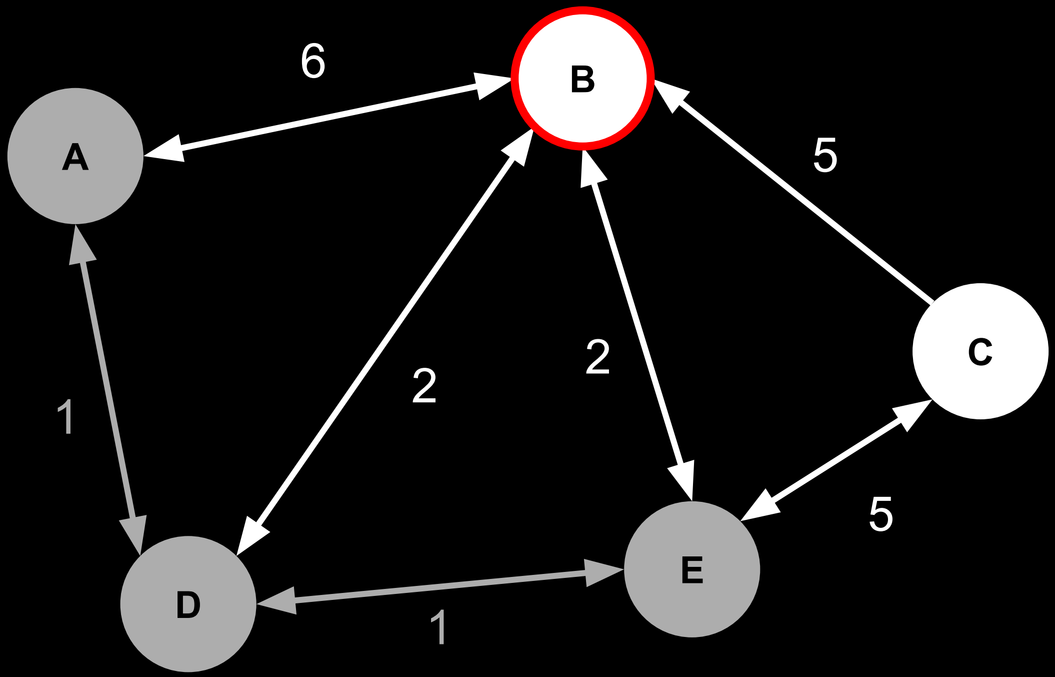


Move to B as new location

Mark E as visited

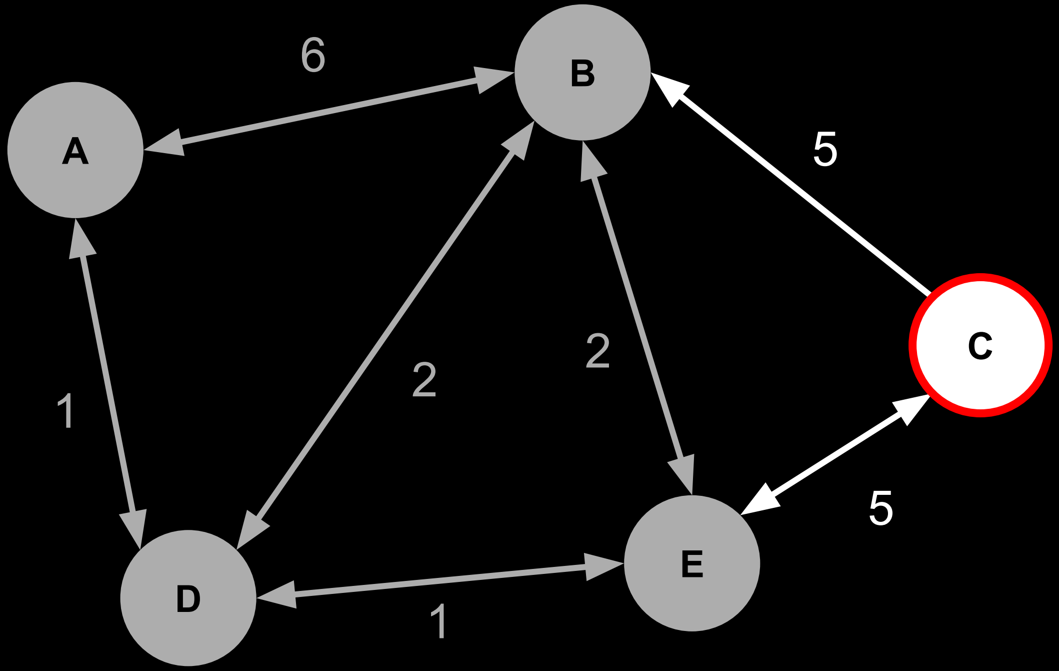
Distances: A = 0, B = 3, C = 7, D = 1, E = 2

No further locations reachable from B



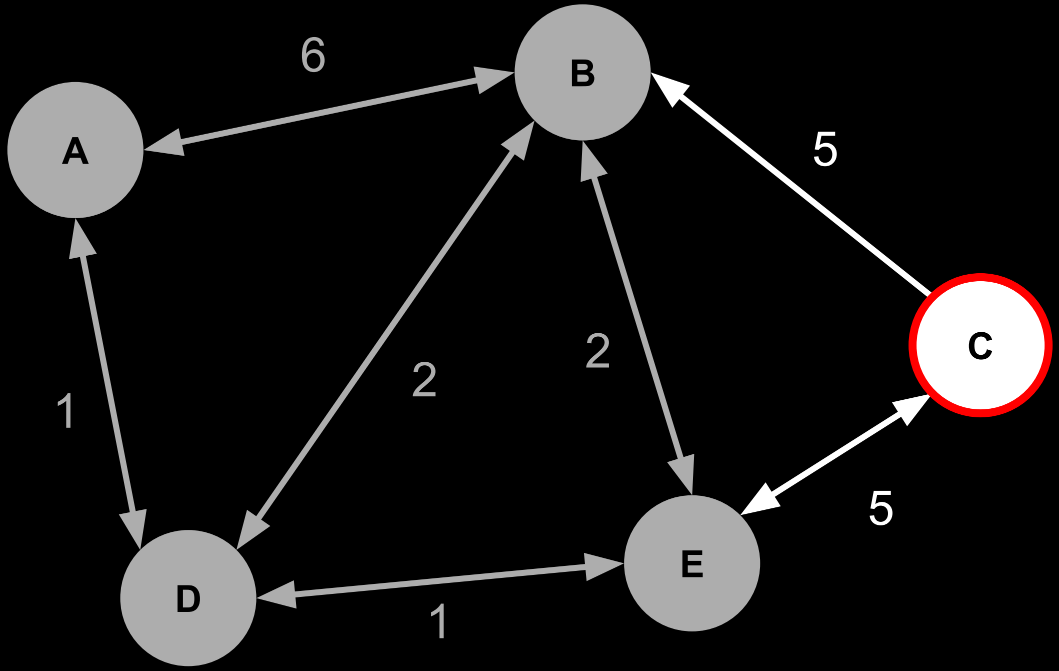
Distances: A = 0, B = 3, C = 7, D = 1, E = 2

Move to C as new location

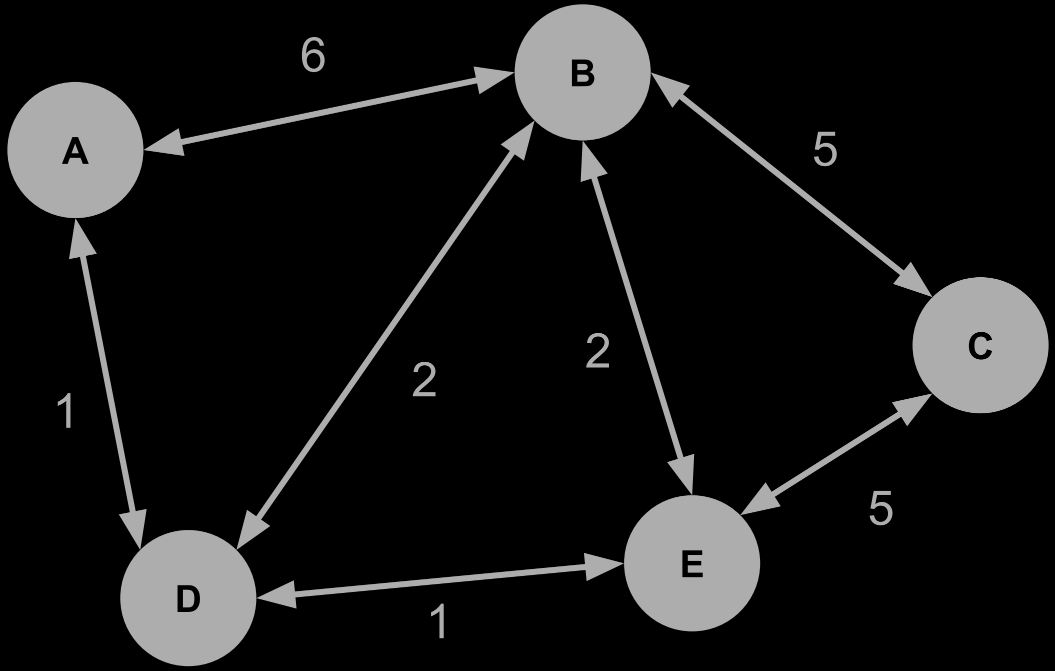


Distances: A = 0, B = 3, C = 7, D = 1, E = 2

No further locations reachable from C



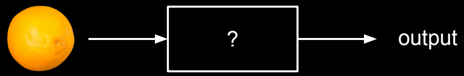
Distances: A = 0, B = 3, C = 7, D = 1, E = 2



All nodes visited, we're done!

input
?
output

spam emails



?

output

finding oranges in images

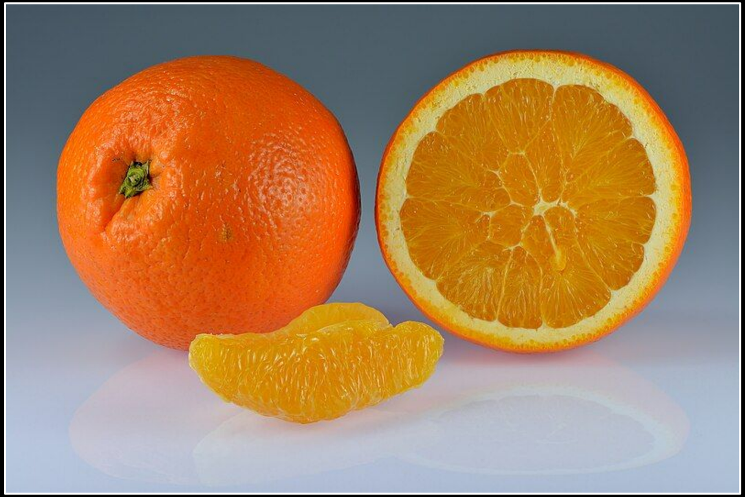


Image source: Wikimedia

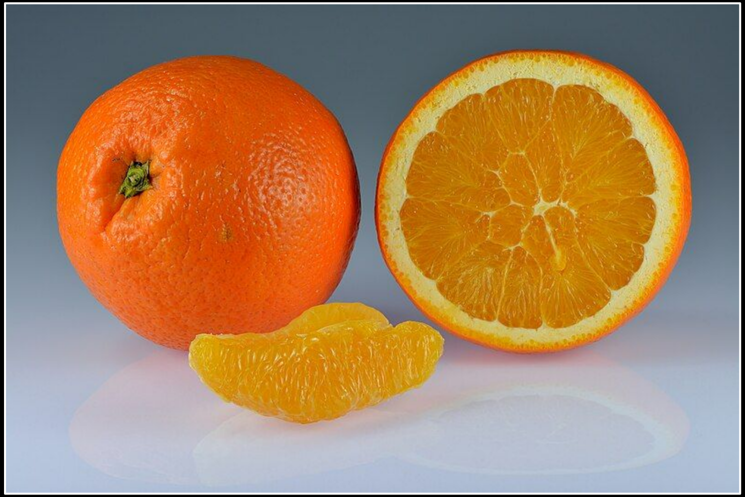
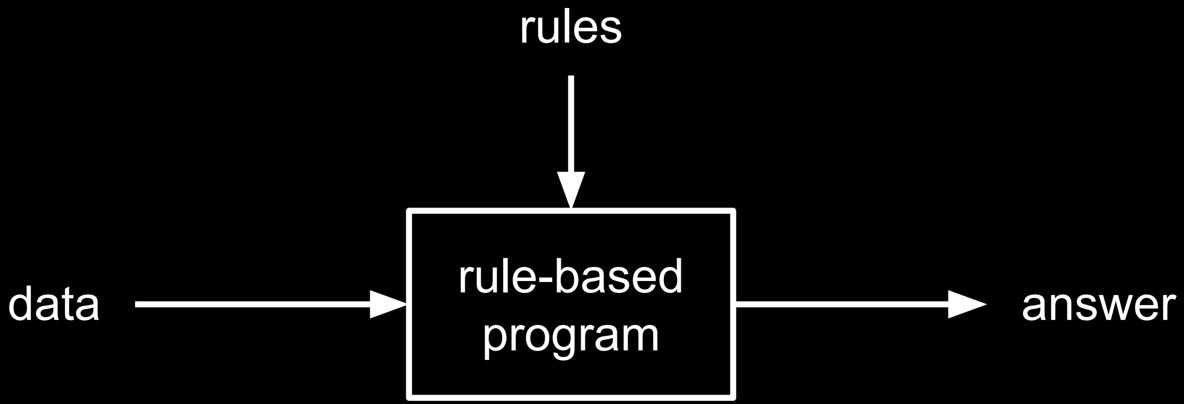


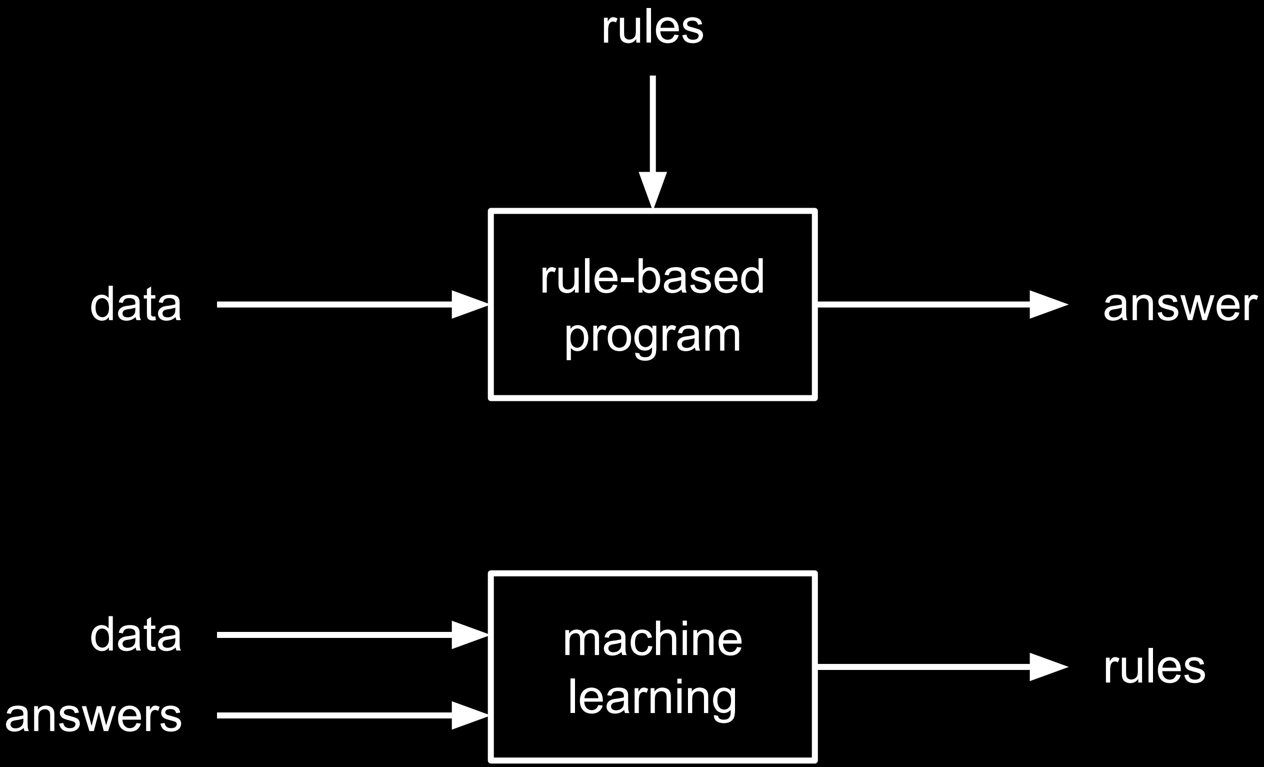
Image source: Wikimedia

Image source: Wikimedia

what set of rules can solve this?

machine learning algorithms


rules
data
rule-based program
answer



rules

data

rule-based program

answer

data

answers

machine learning

rules