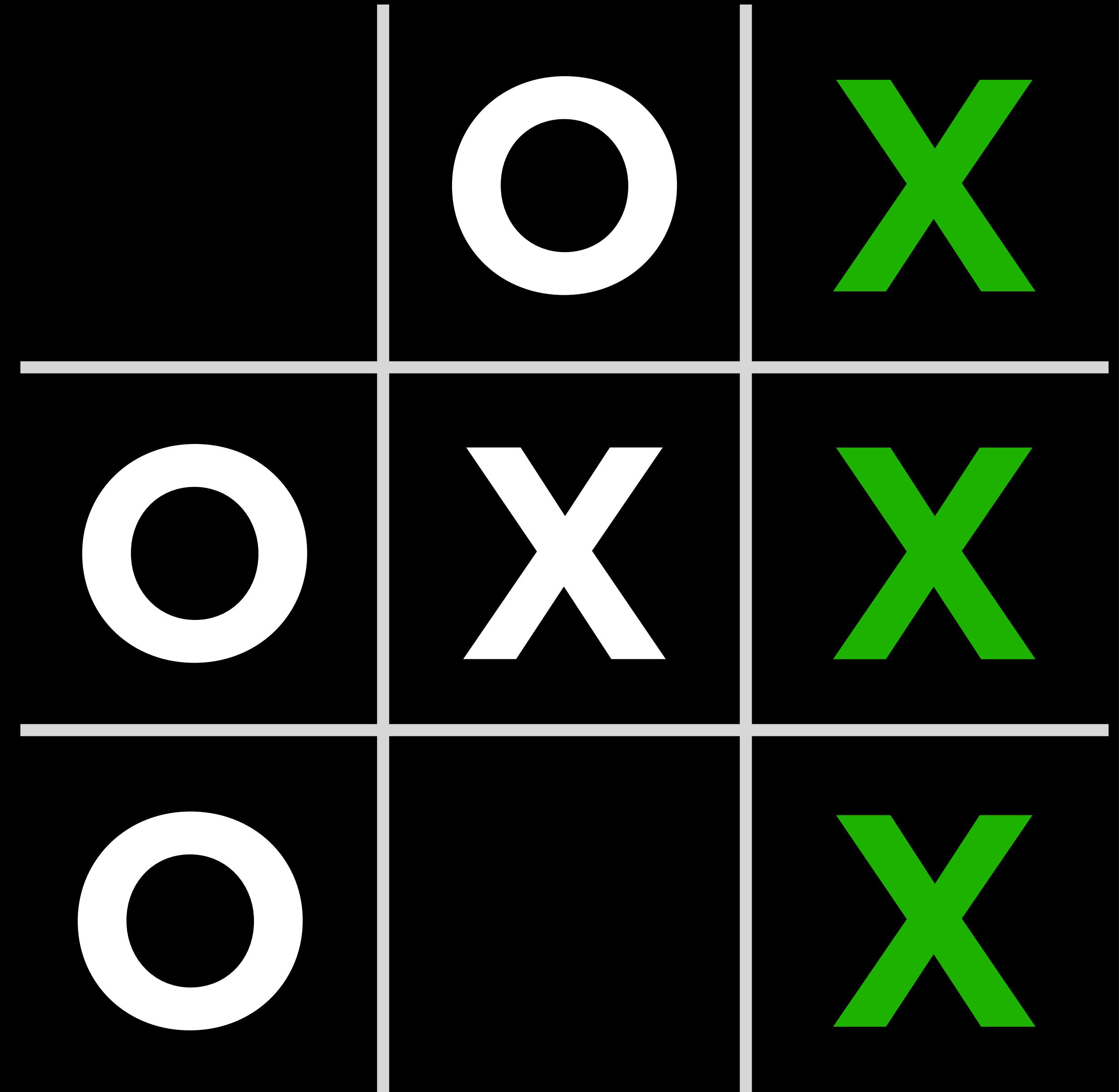
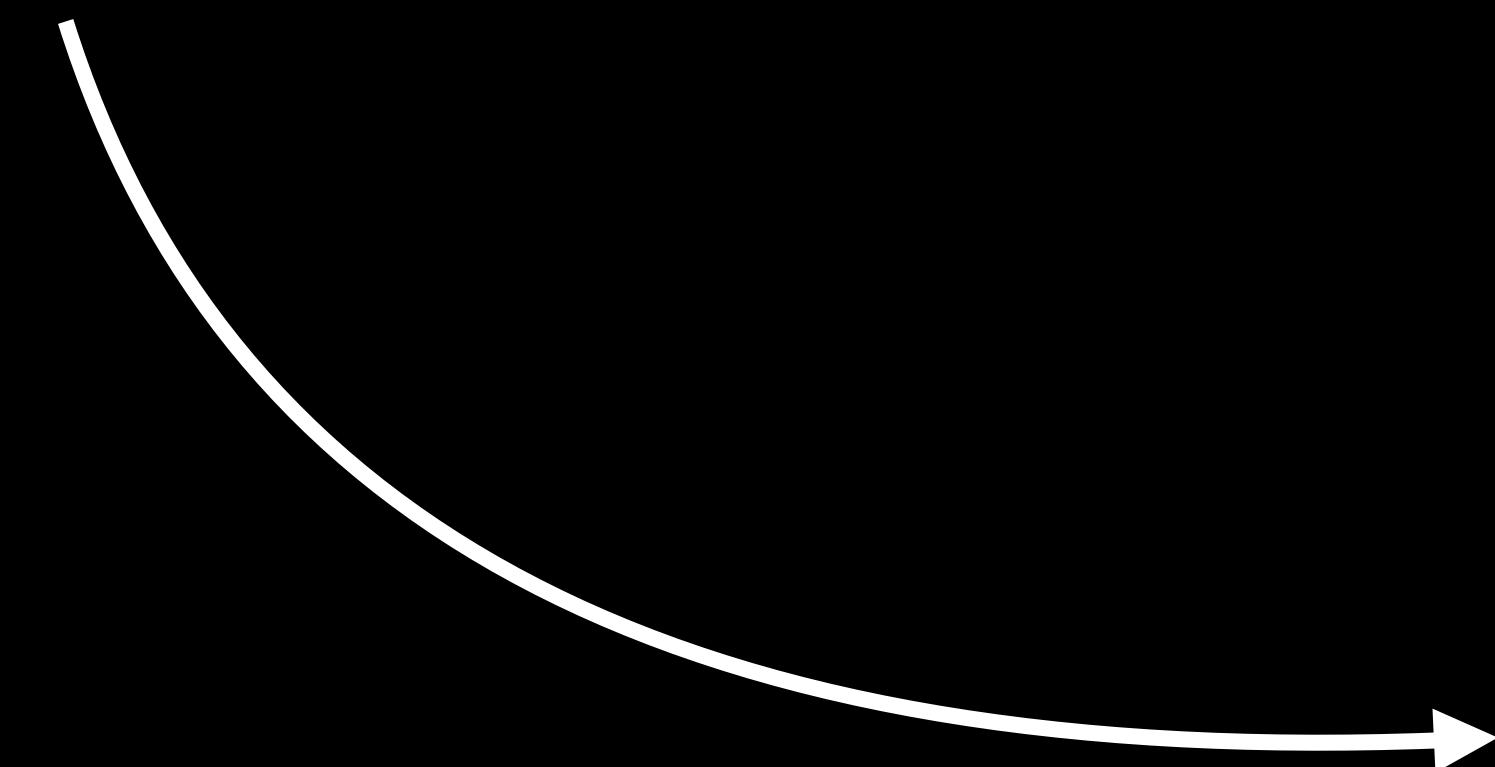


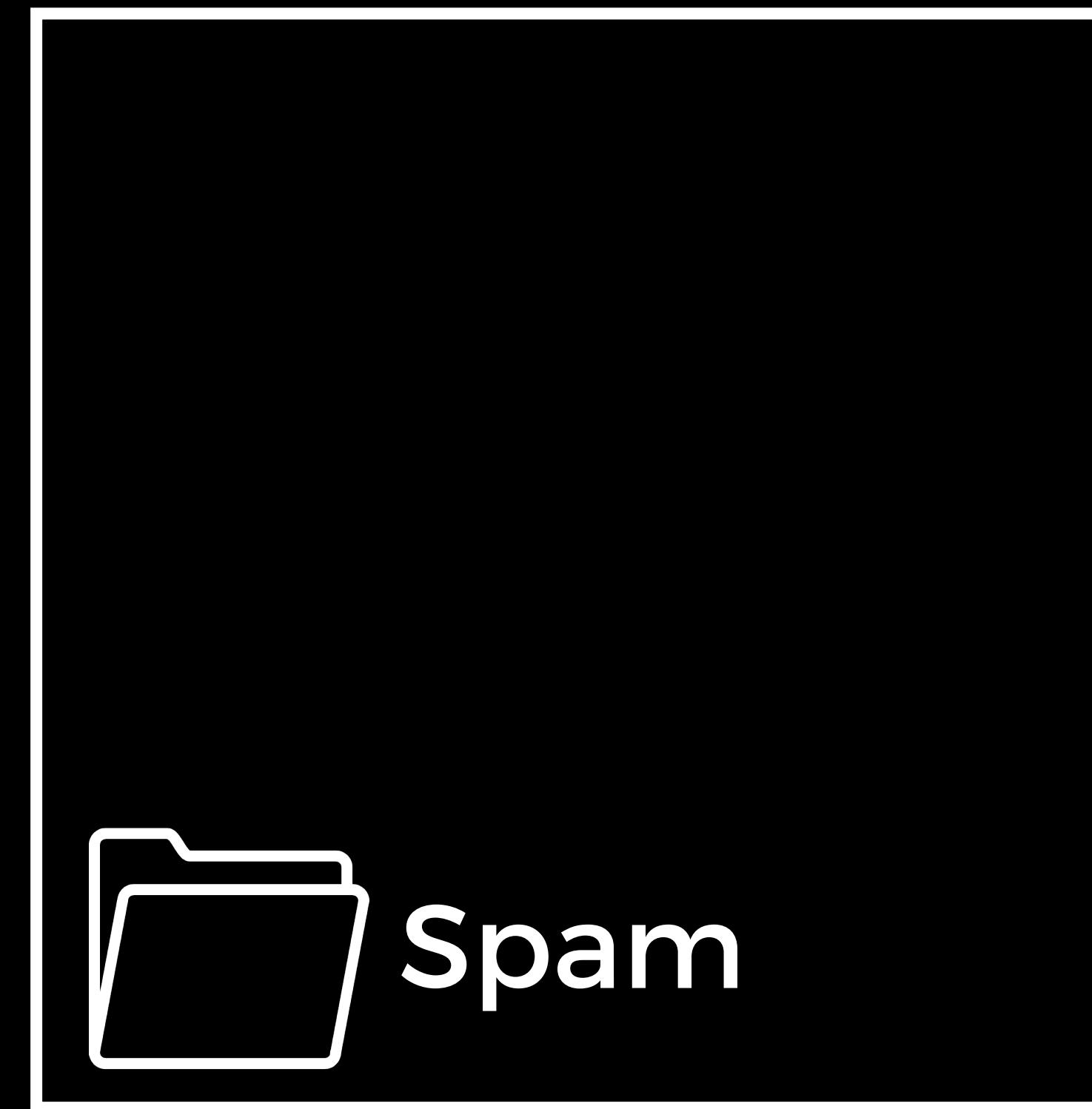
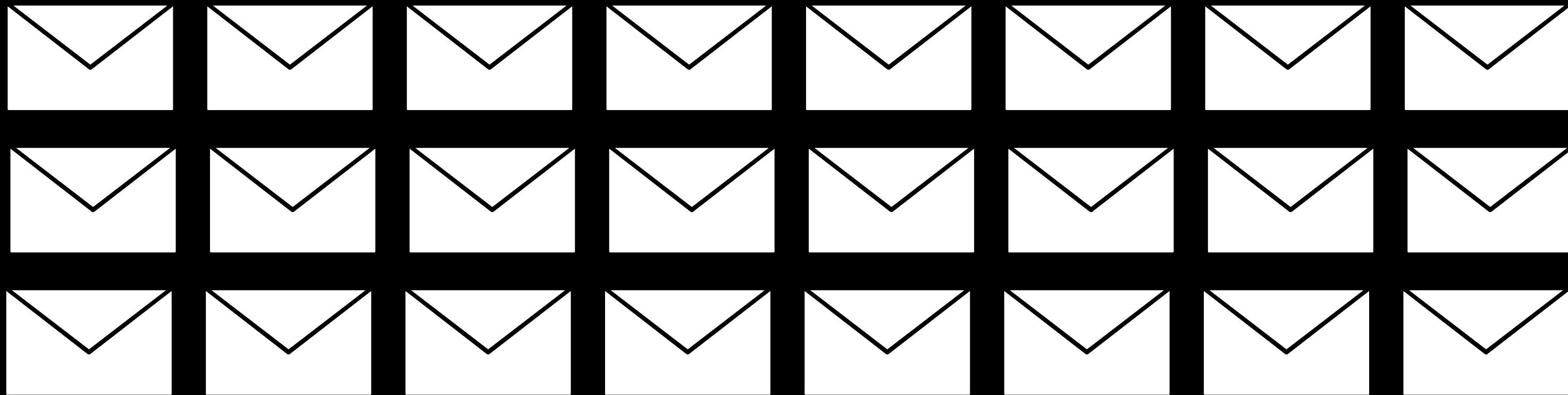
# Artificial Intelligence

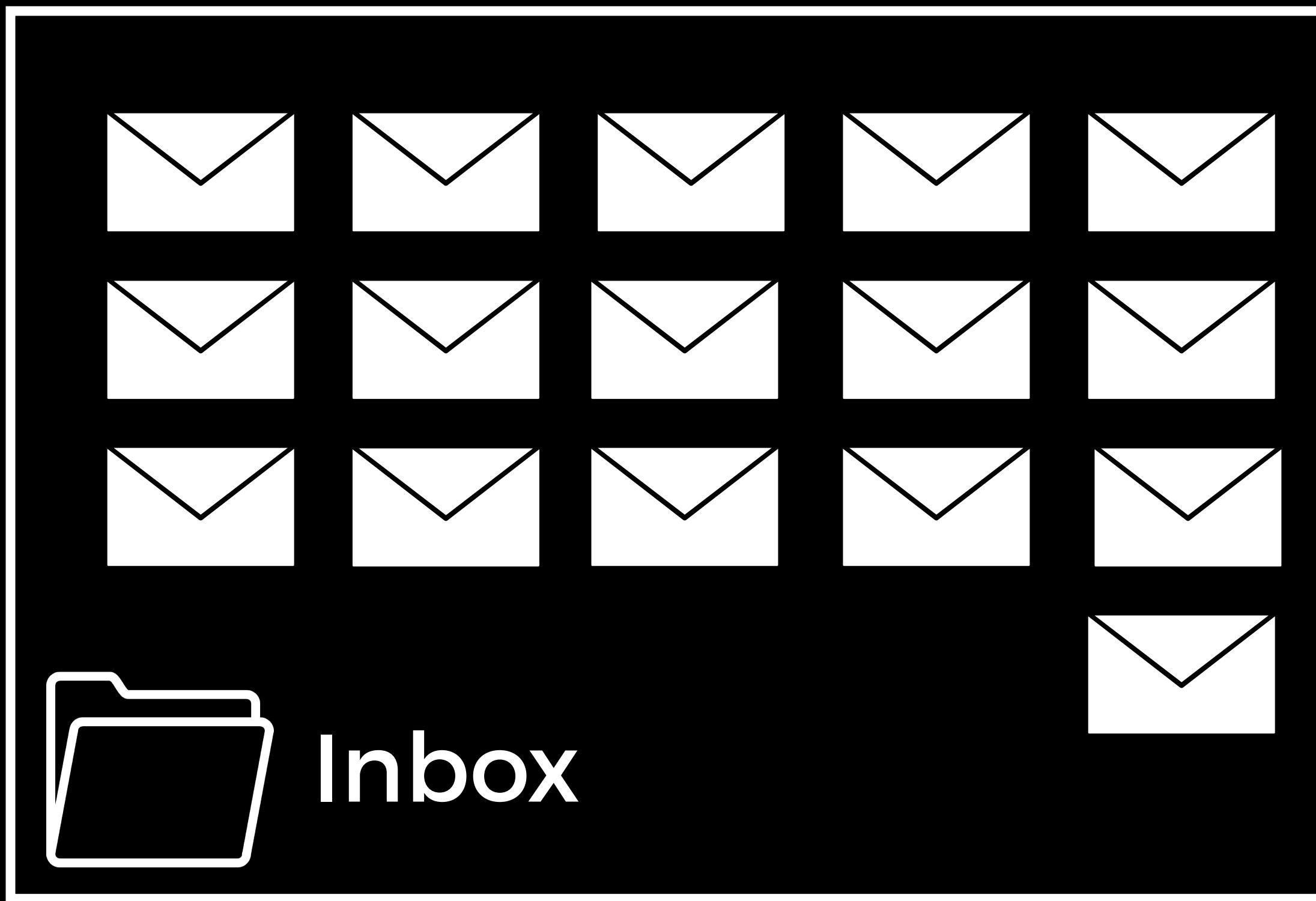


handwriting

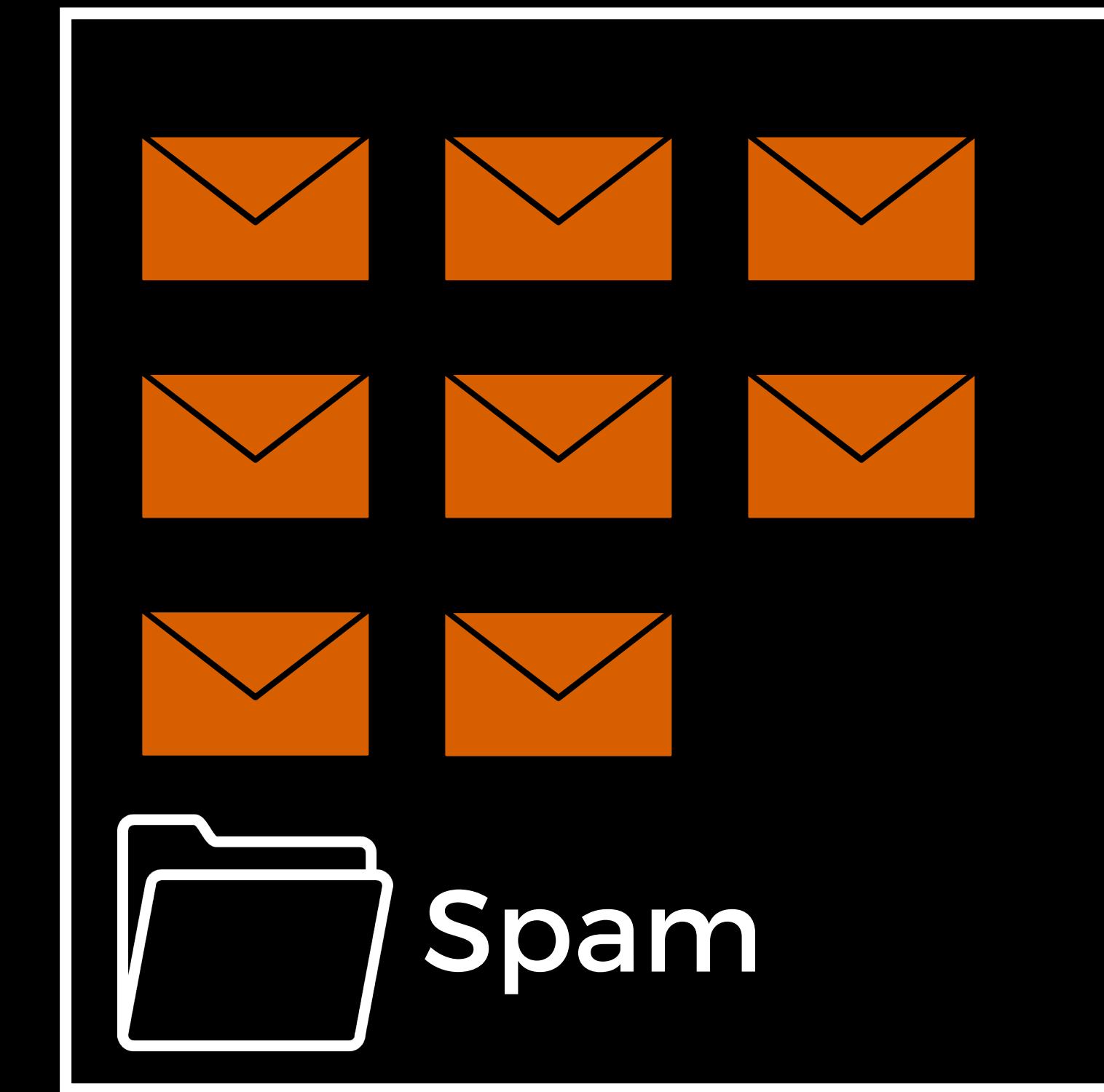


handwriting

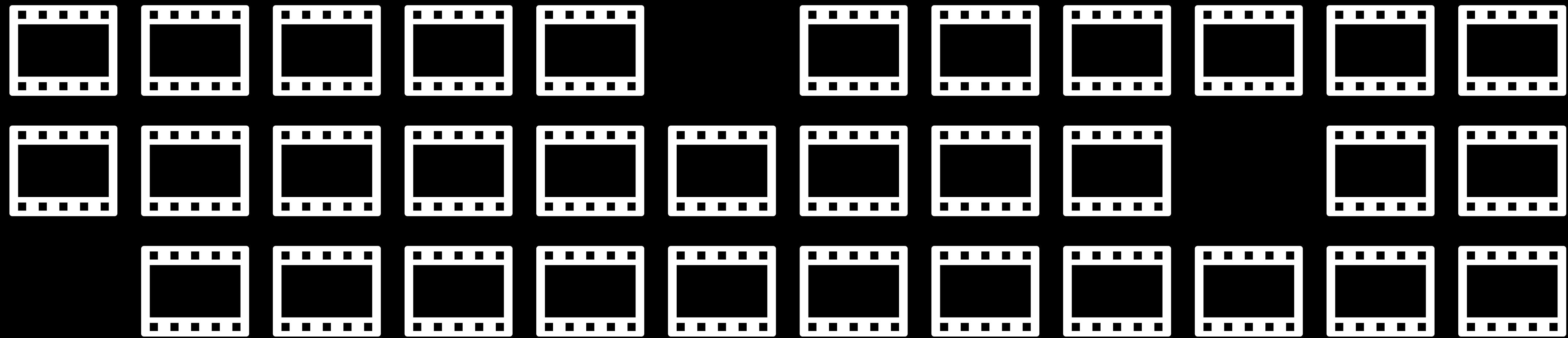




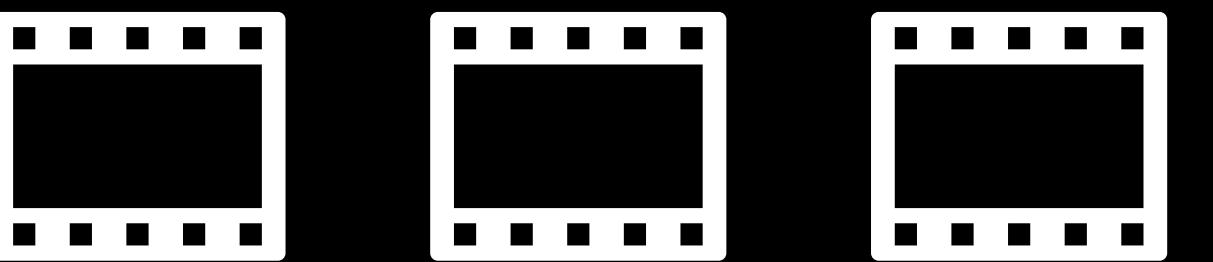
Inbox



Spam



Watch History



Recommended



Image 1

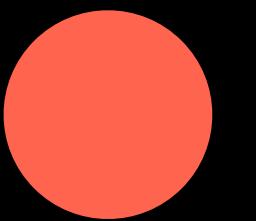
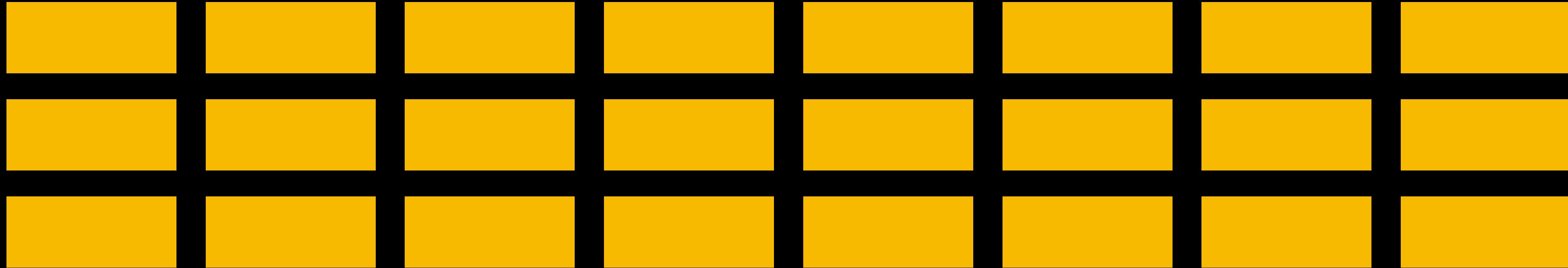


Image 2



# Artificial Intelligence

# Decision-Making



# Decision Trees

Is ball left of paddle?

Yes

Move paddle left.

No

Is ball right of paddle?

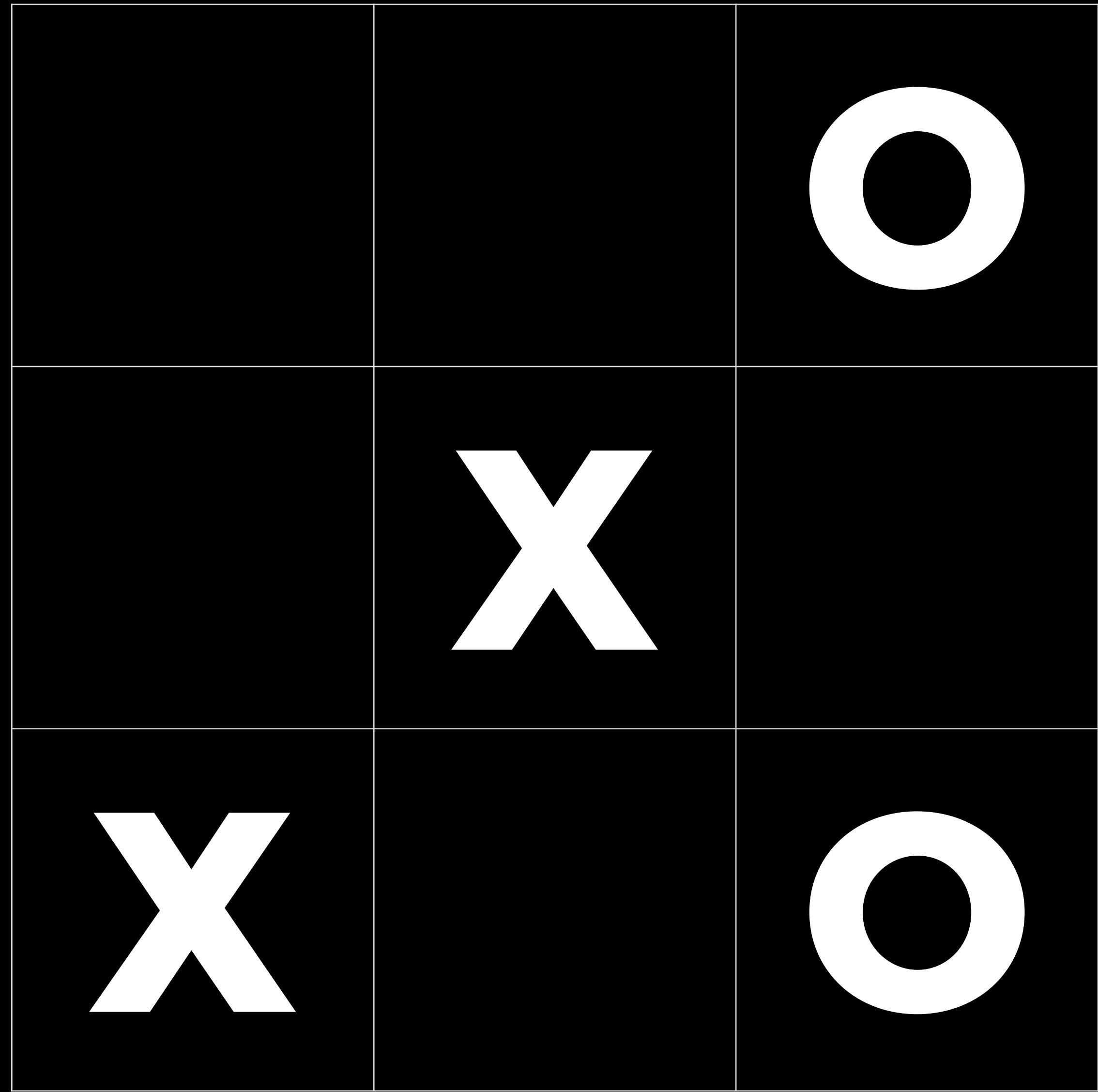
Yes

Move paddle right.

No

Don't move paddle.

```
while game is ongoing:  
    if ball left of paddle:  
        move paddle left  
    else if ball right of paddle:  
        move paddle right  
    else:  
        don't move paddle
```



Can I get 3 in a row on  
this turn?

Yes

No

Play in square to get 3  
in a row.

Can my opponent get 3  
in a row on next turn?

Yes

No

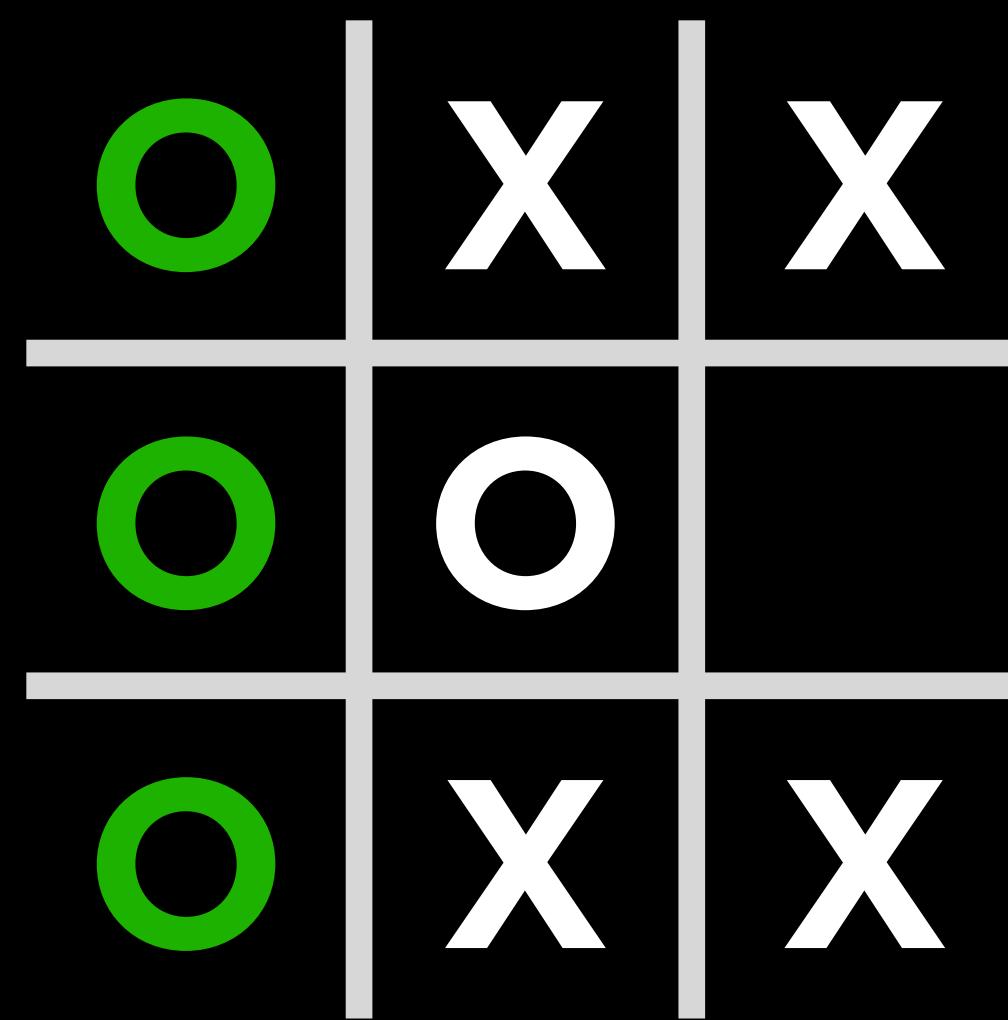
Play in square to block  
opponent's 3 in a row.

?

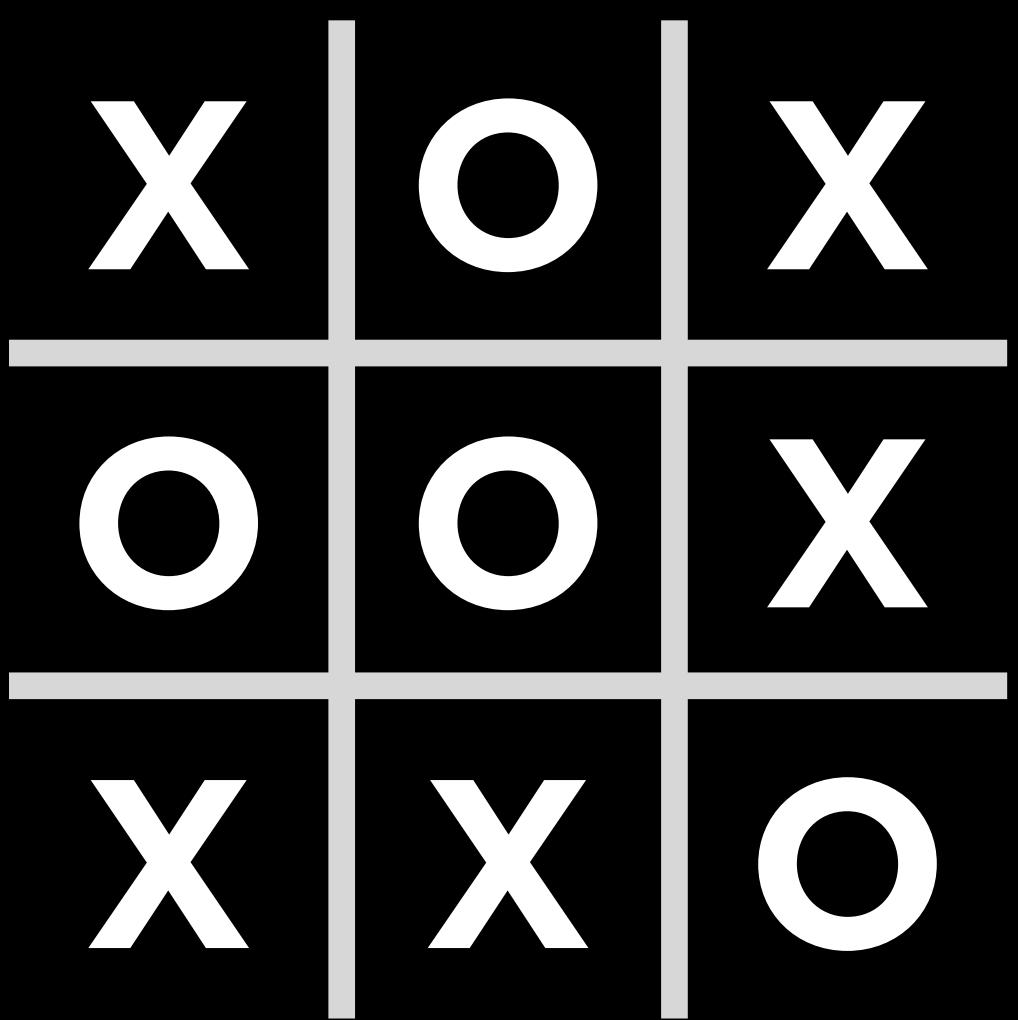
# Optimal Decision-Making

# Minimax

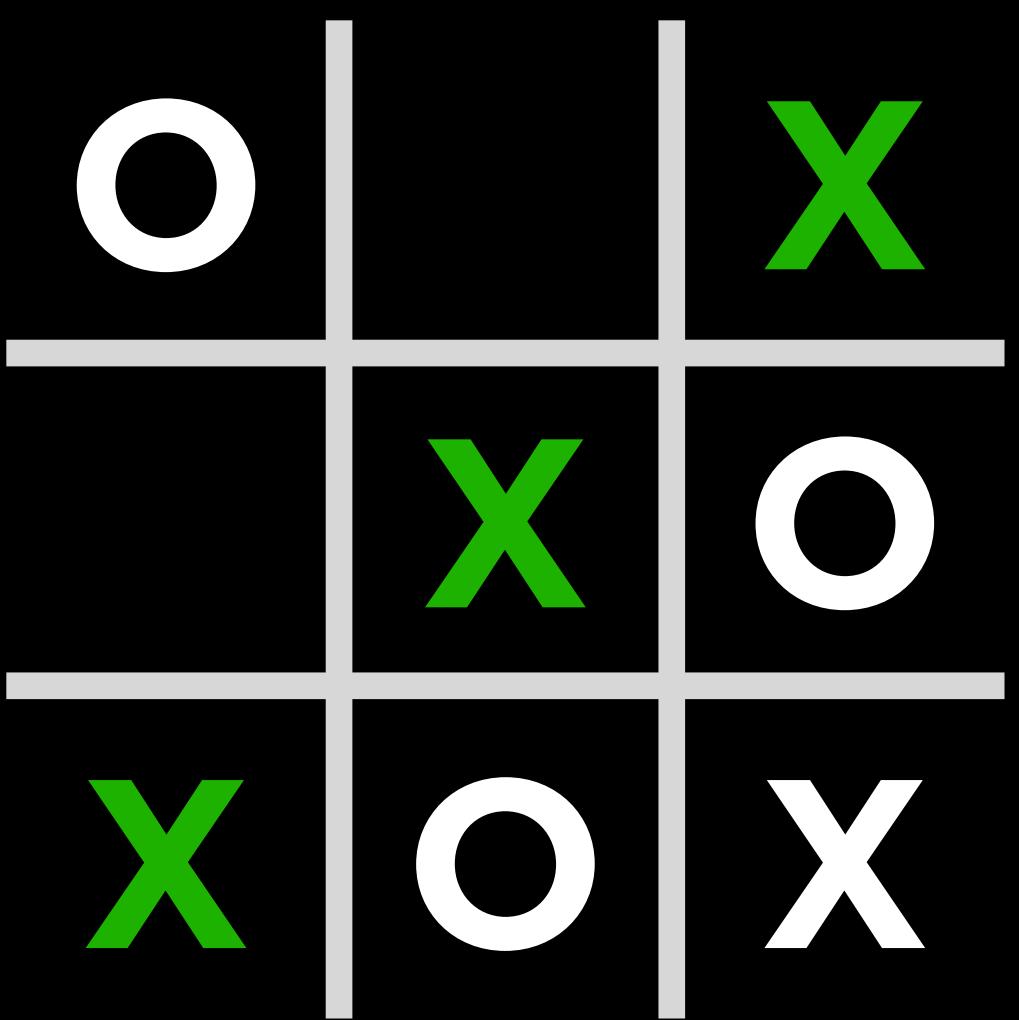
- MAX (X) aims to maximize score.
- MIN (O) aims to minimize score.



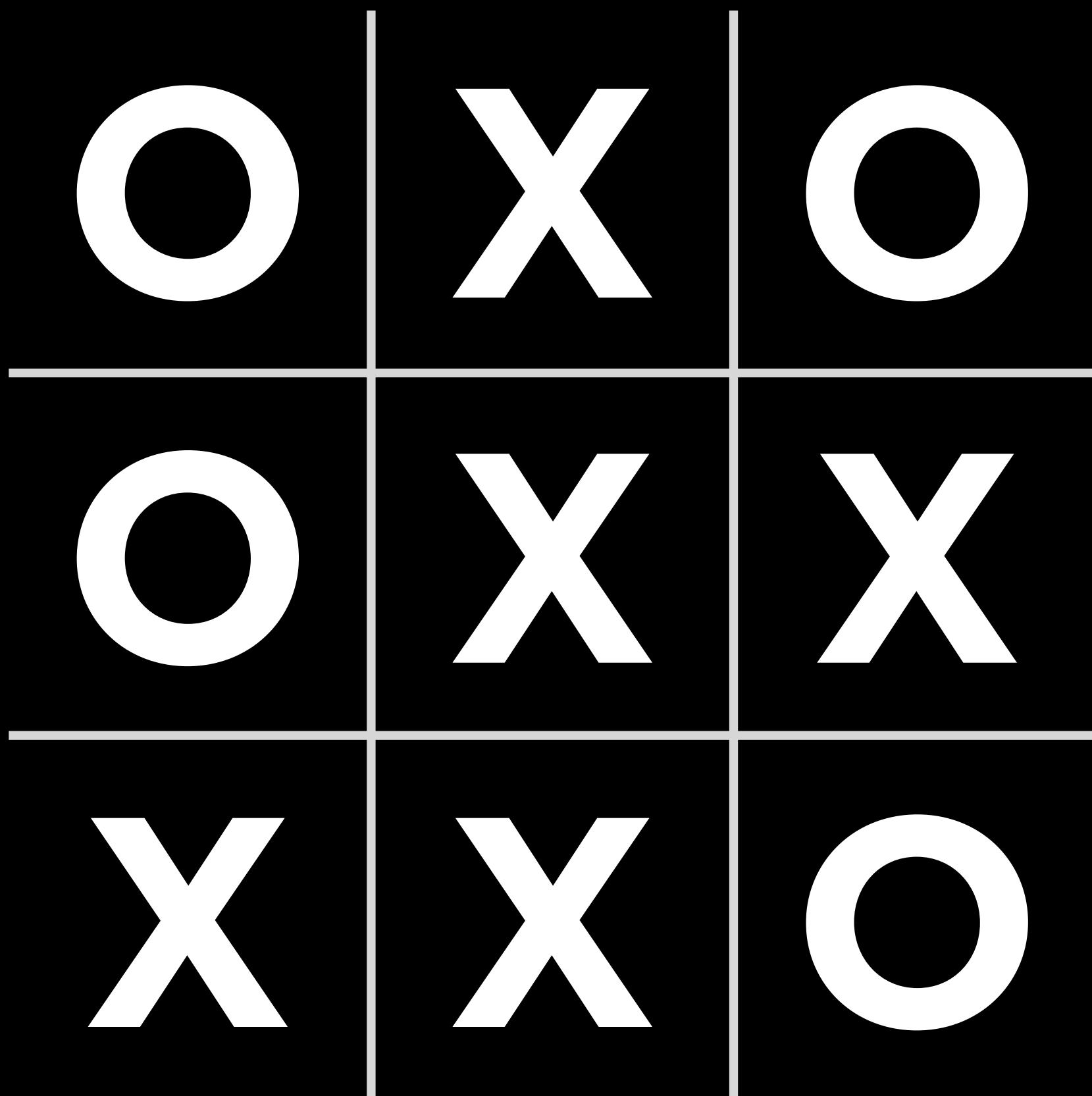
-1



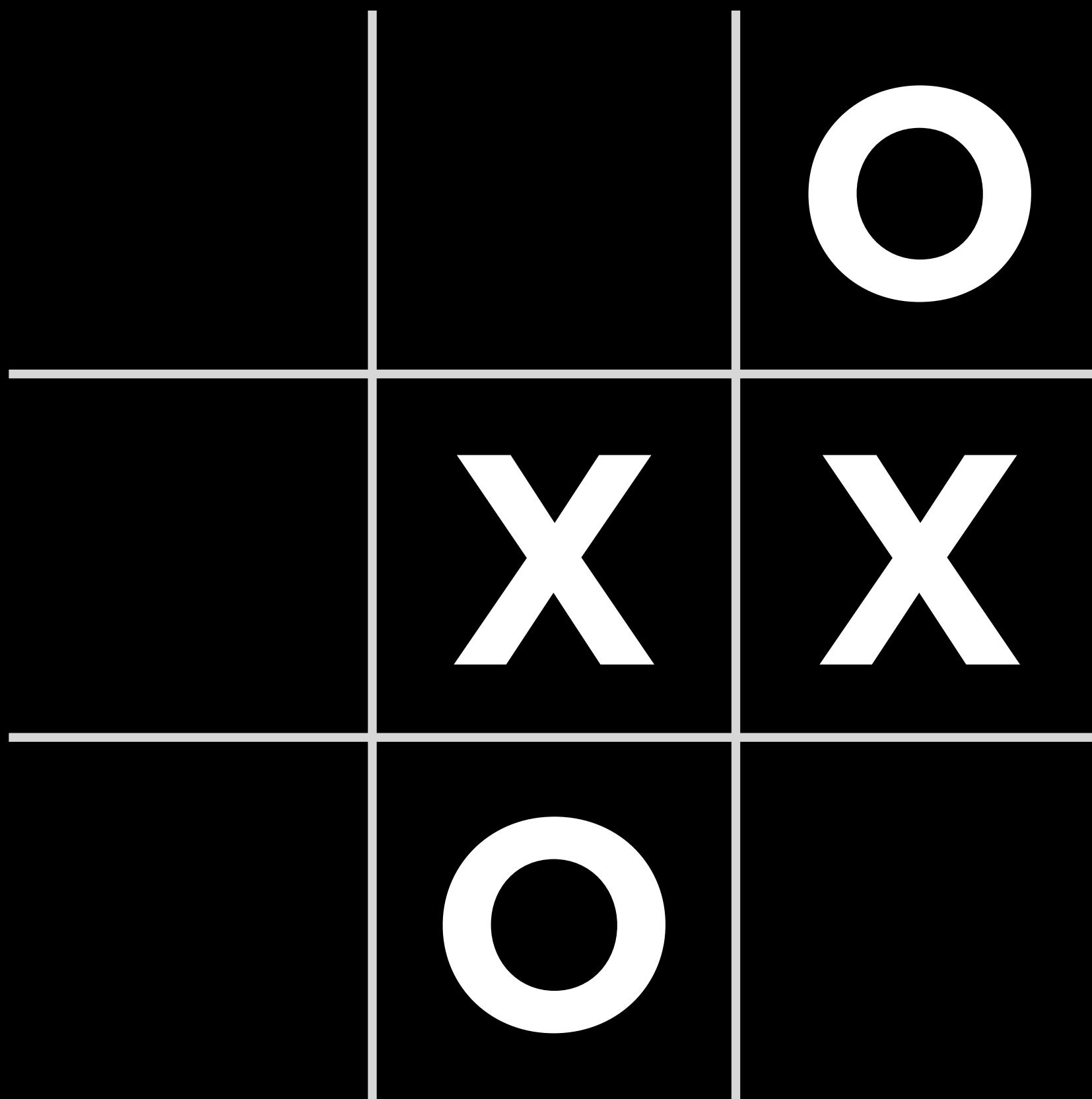
0



1

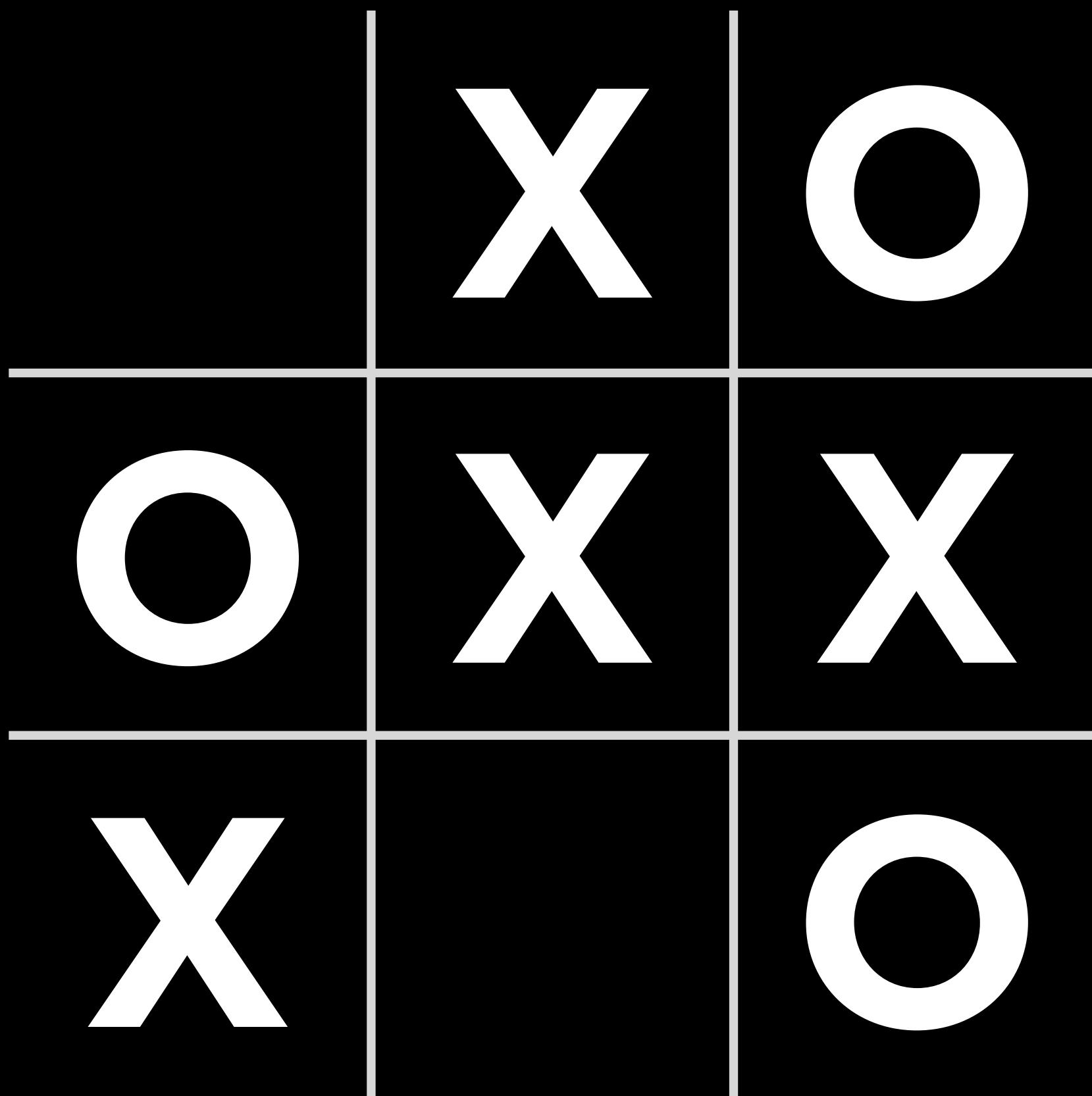


VALUE: 1



X's Turn

VALUE: 1

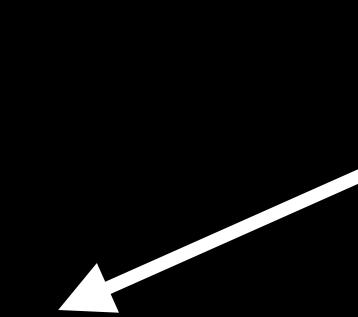


O's Turn

VALUE: ?

Turn: O

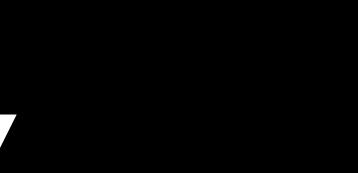
VALUE:	0	X	O
	X	X	X
	X	O	



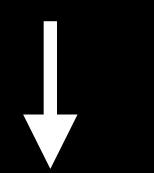
VALUE:	1	O	X	O
	O	X	X	
	X		O	



VALUE:	0	X	O
	O	X	X
	X	O	O

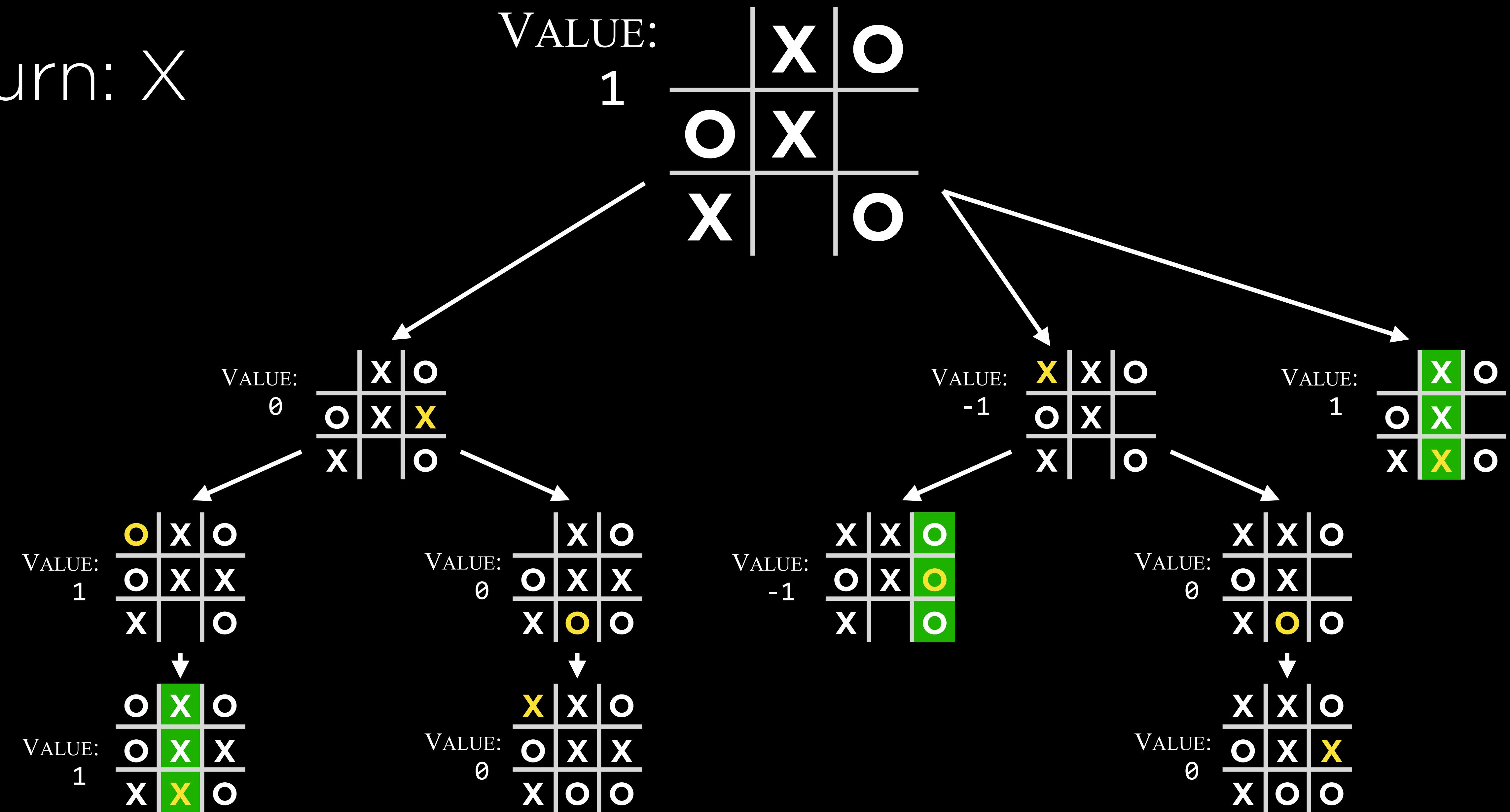


VALUE:	1	O	X	O
	O	X	X	
	X	X	O	



VALUE:	0	X	X	O
	O	X	X	
	X	O	O	

Turn: X



# Minimax

```
if player is X:  
    for all possible moves:  
        calculate score for board  
        choose move with highest score  
  
else:  
    for all possible moves:  
        calculate score for board  
        choose move with lowest score
```

255,168

total possible Tic-Tac-Toe games



288,000,000,000

total possible chess games  
after four moves each

$10^{29000}$

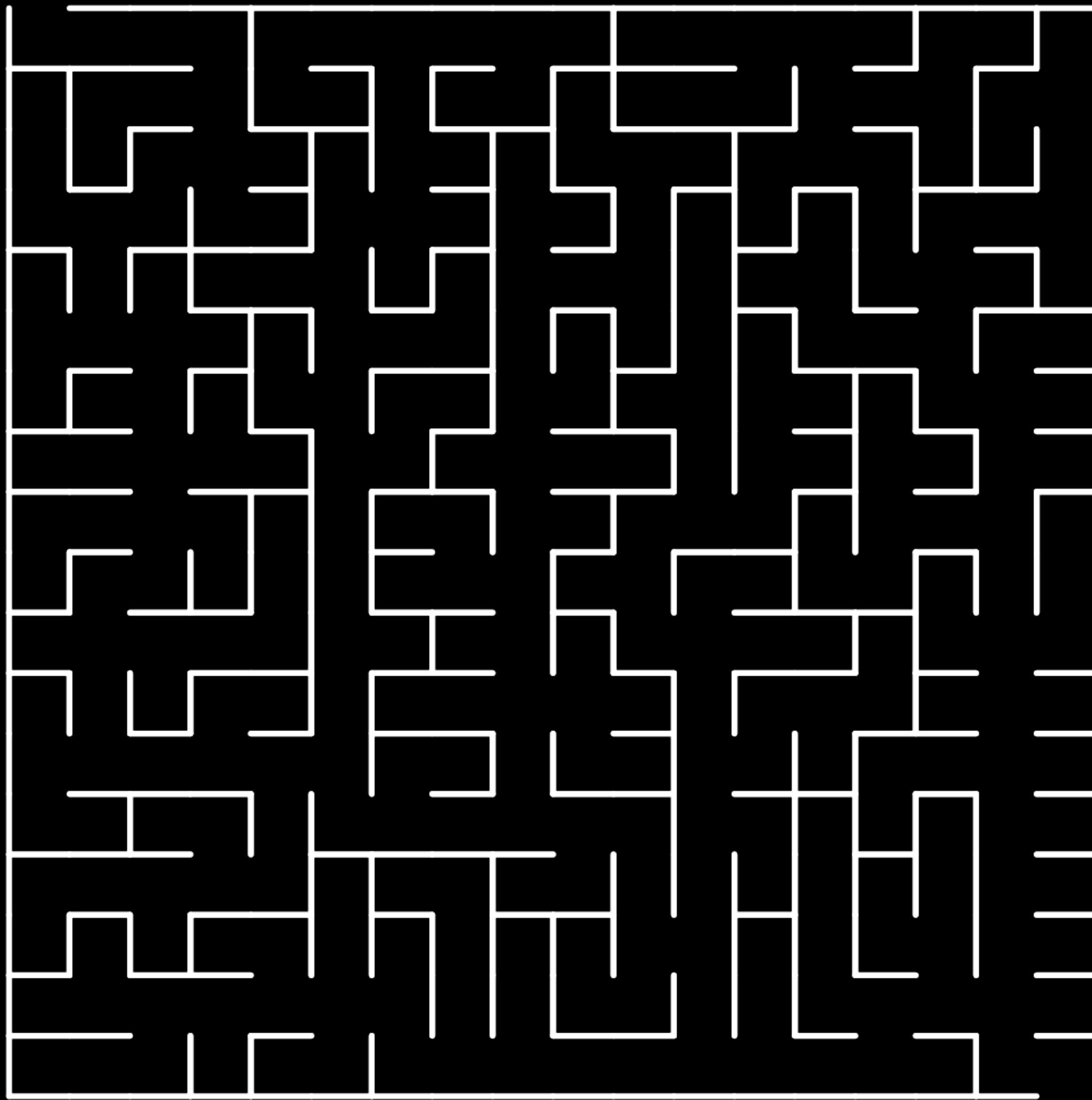
total possible chess games  
(lower bound)

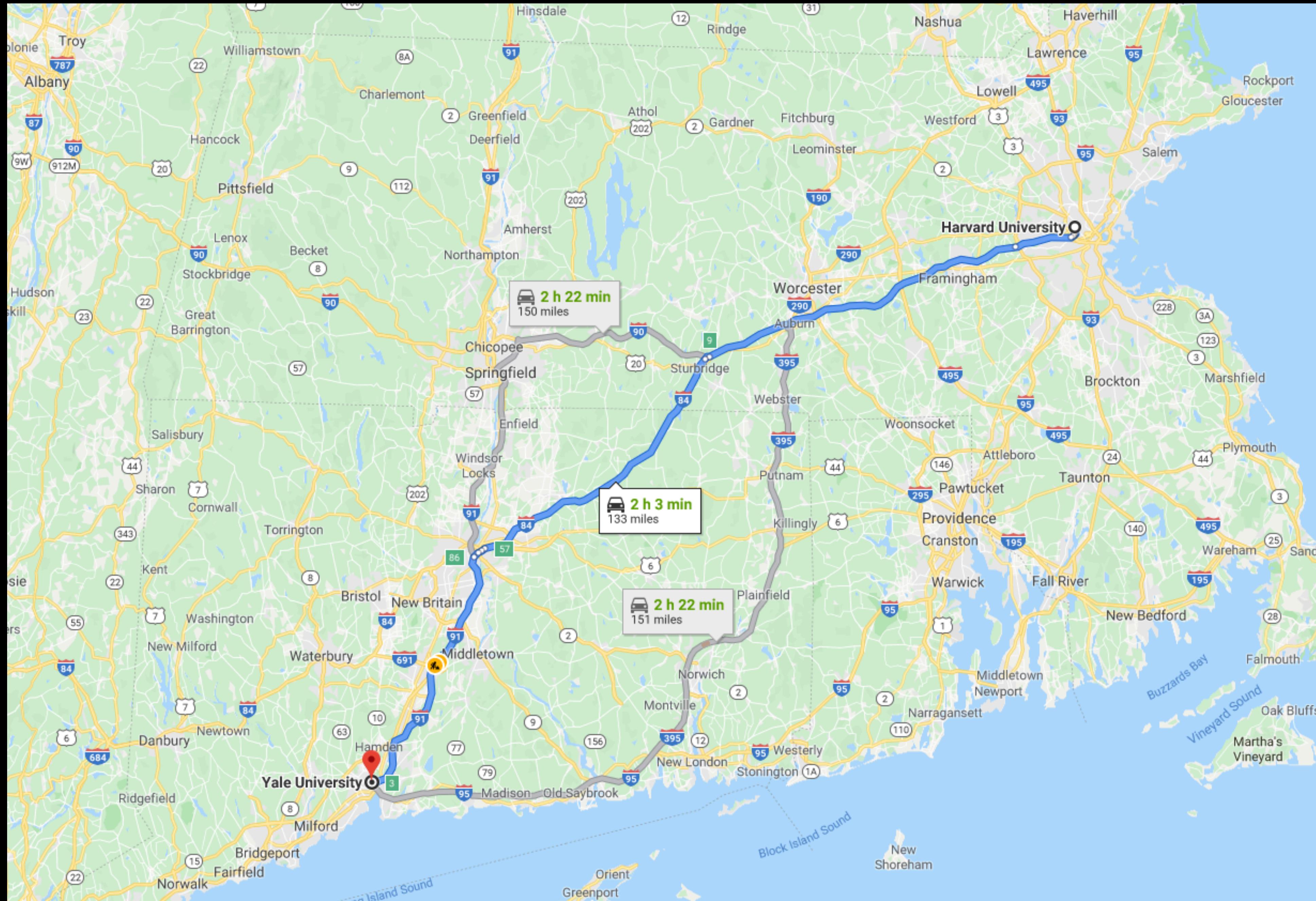
# Depth-Limited Minimax

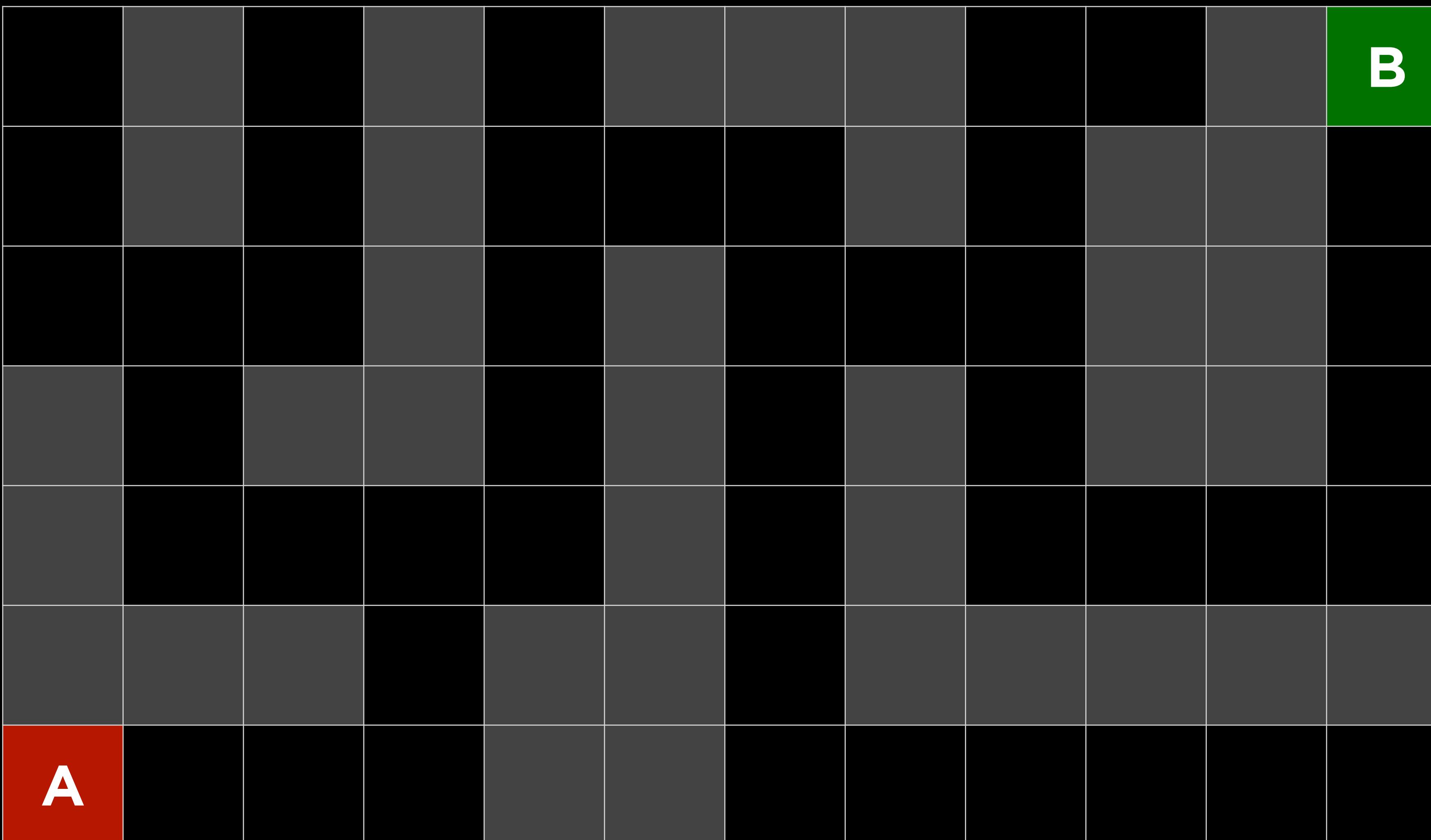
# evaluation function

function that estimates the expected utility  
of the game from a given state

# Search

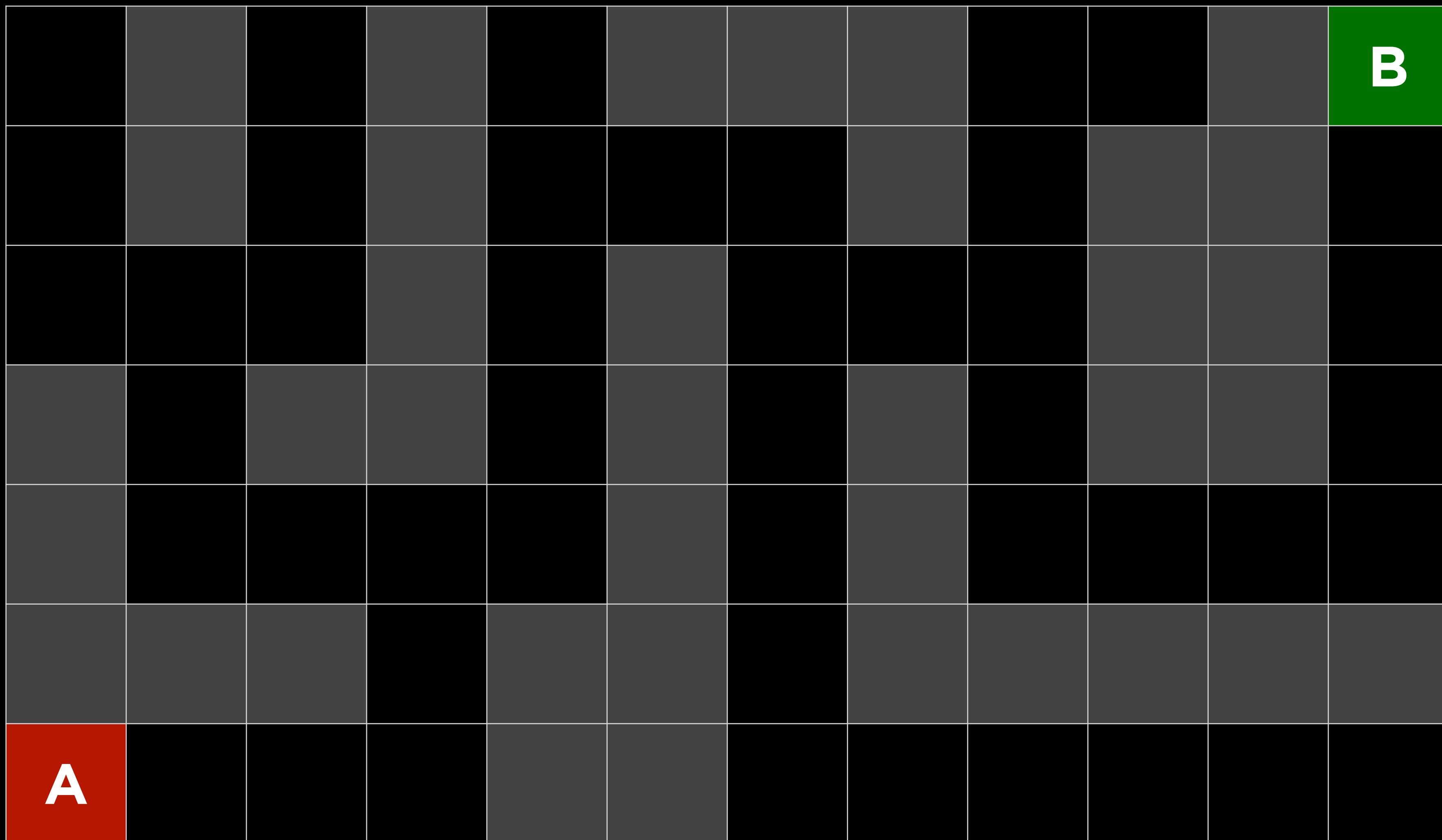




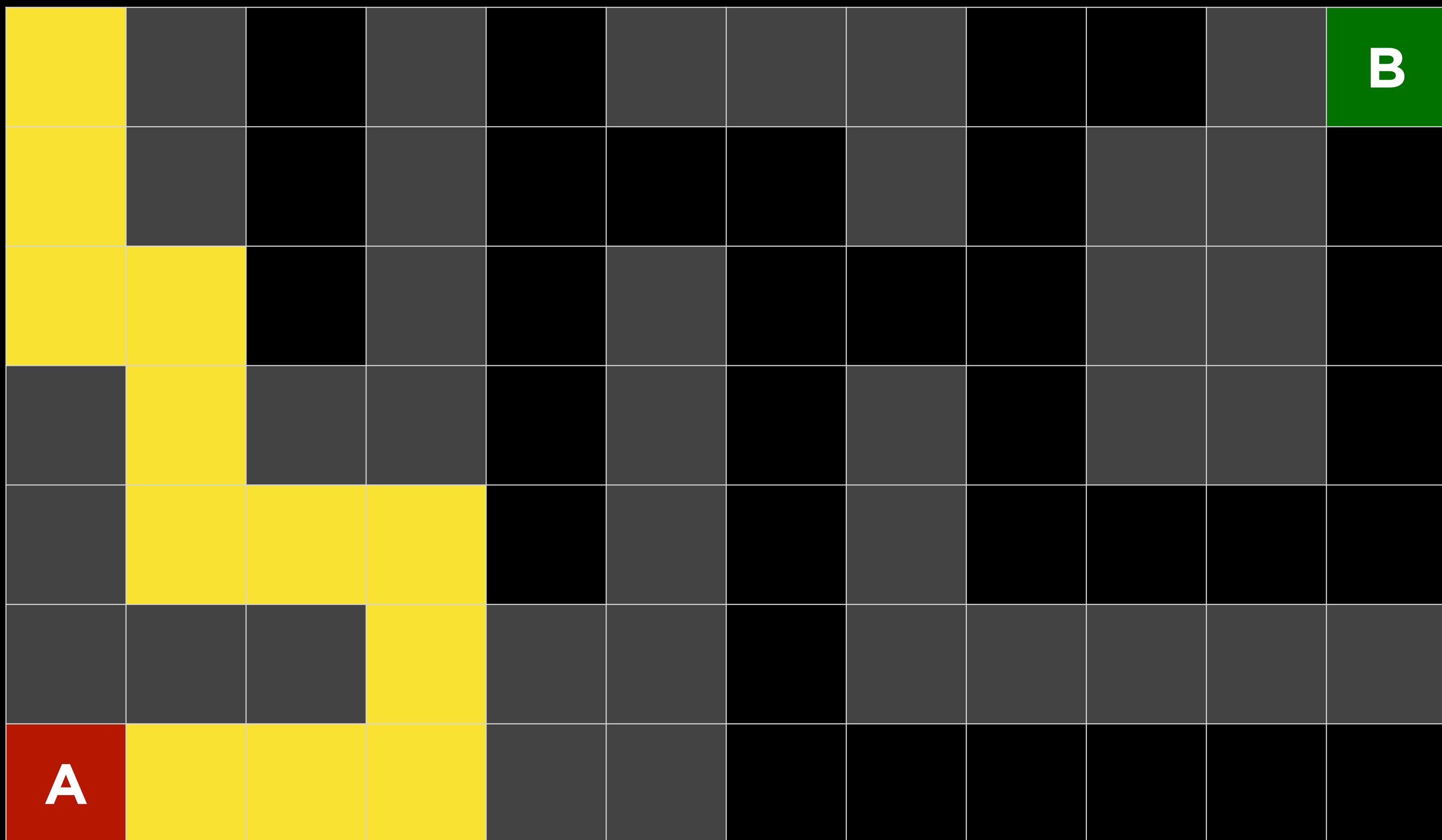


# Depth-First Search

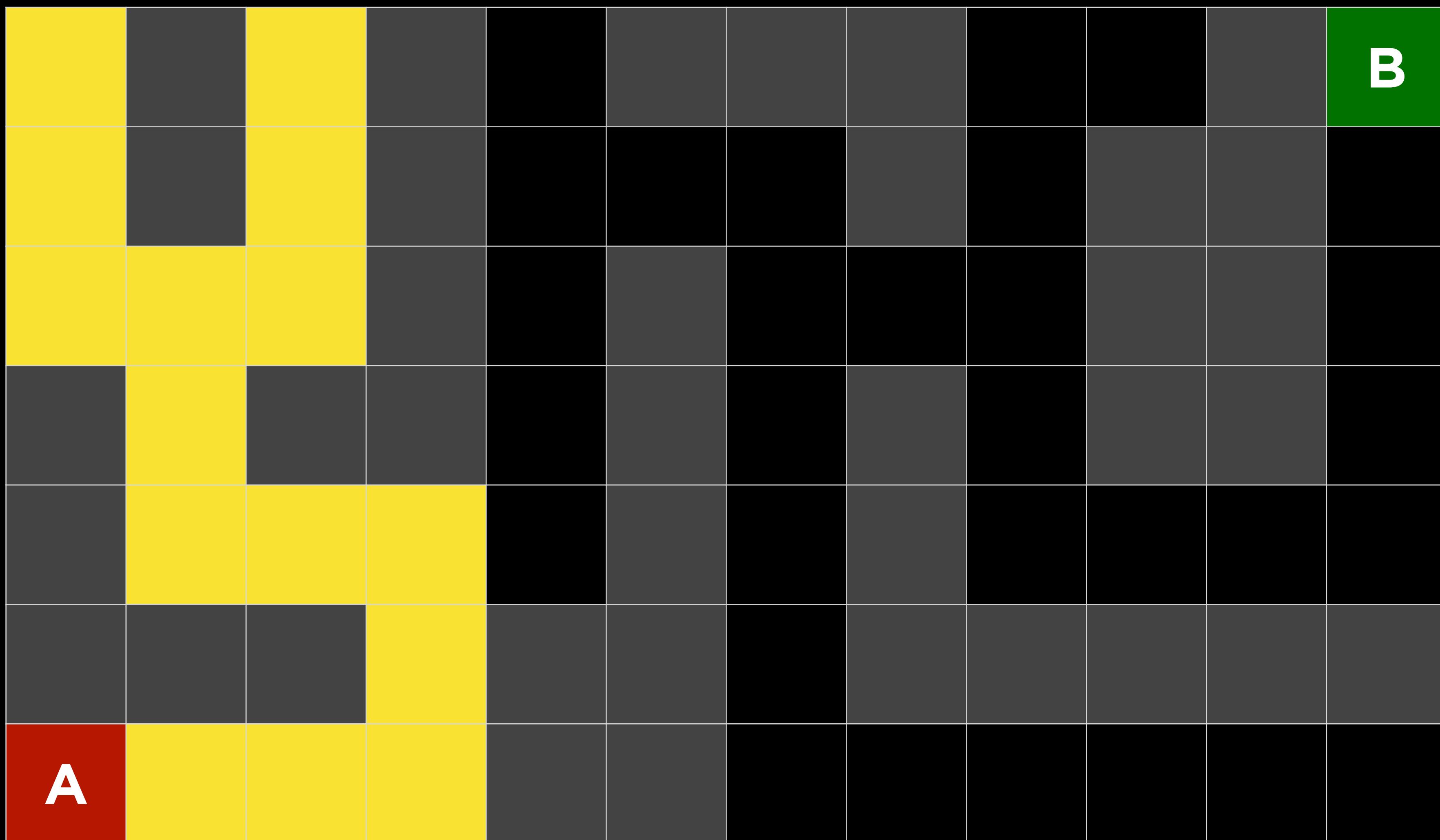
# Depth-First Search



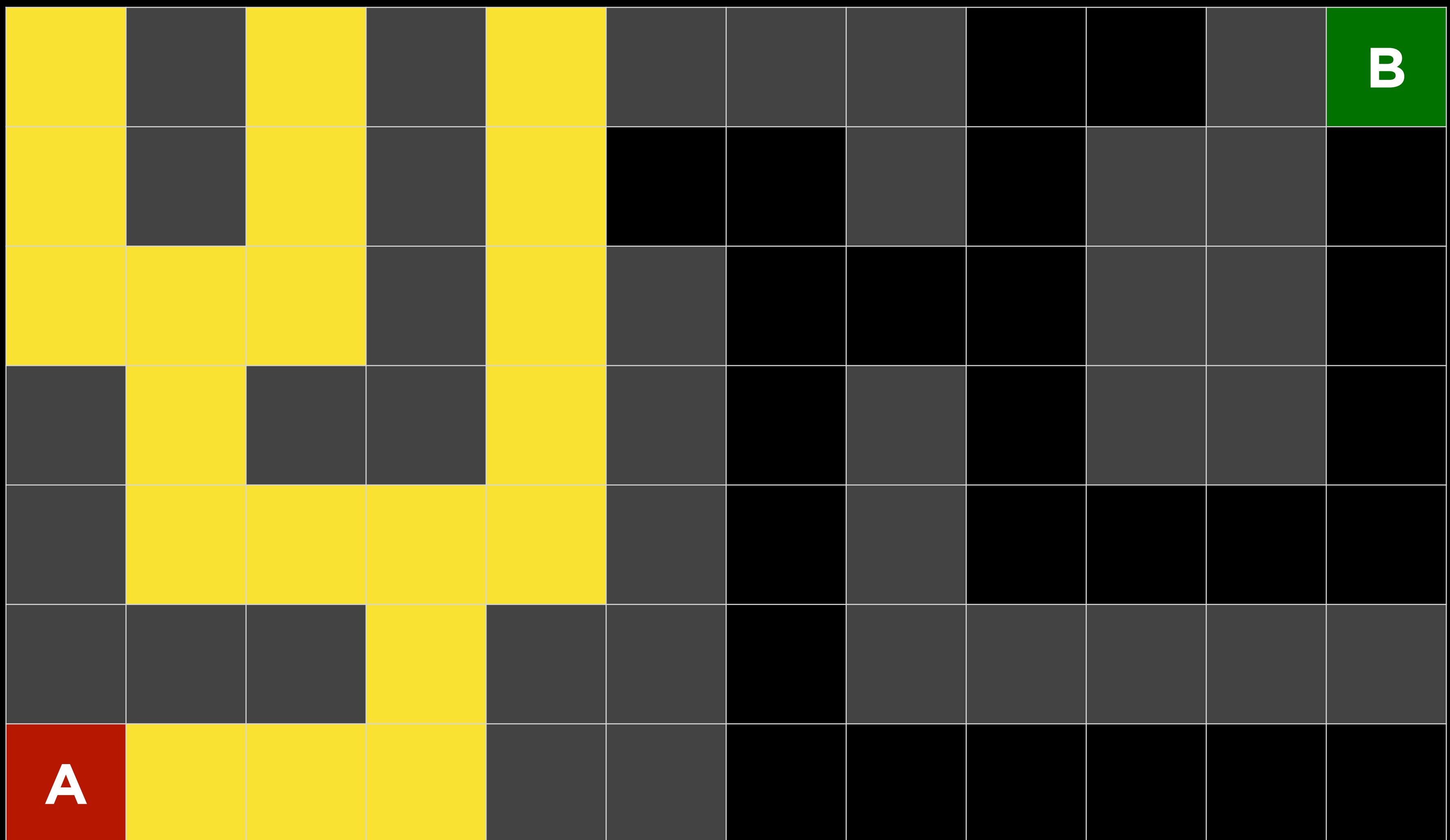
# Depth-First Search



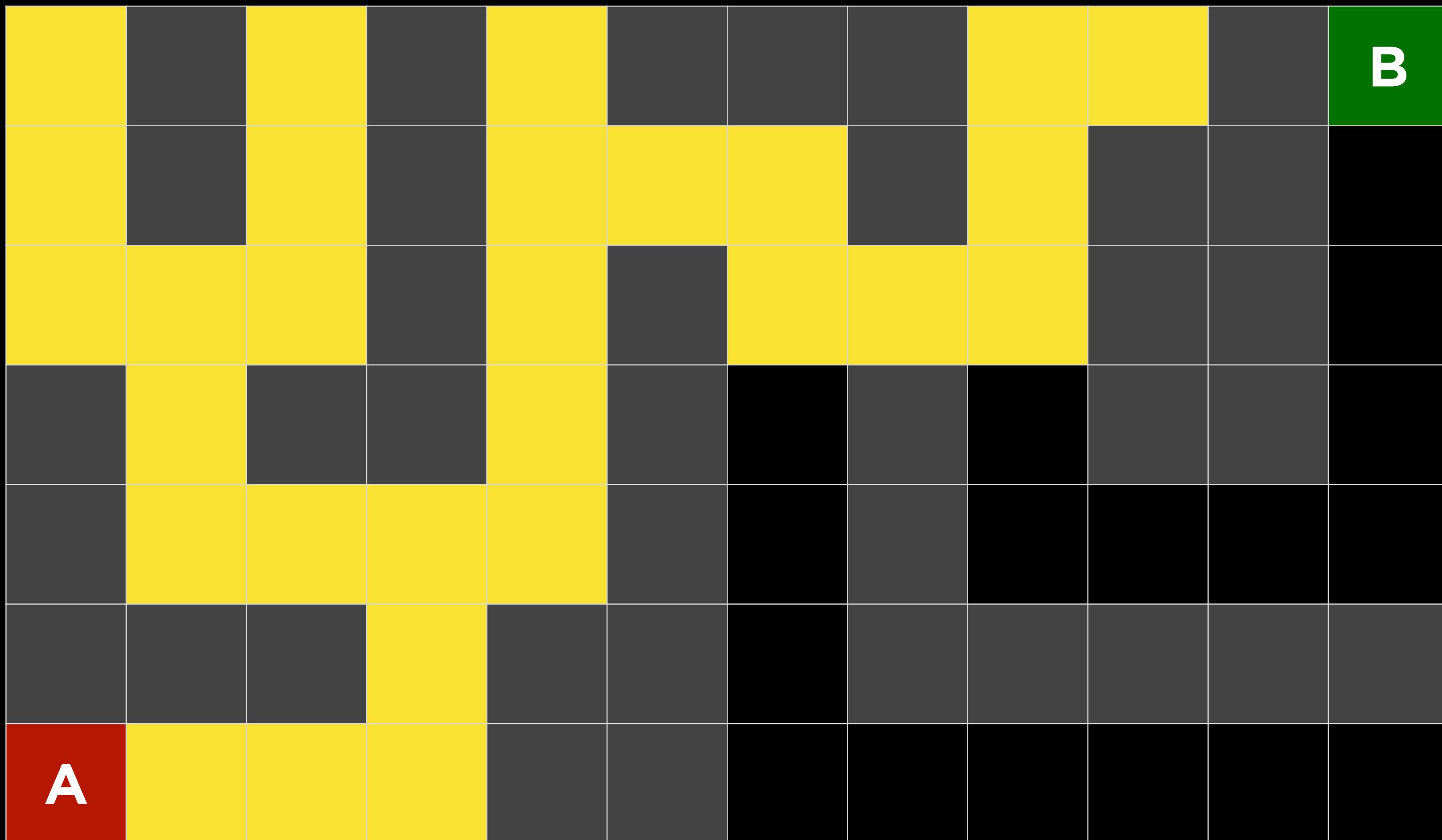
# Depth-First Search



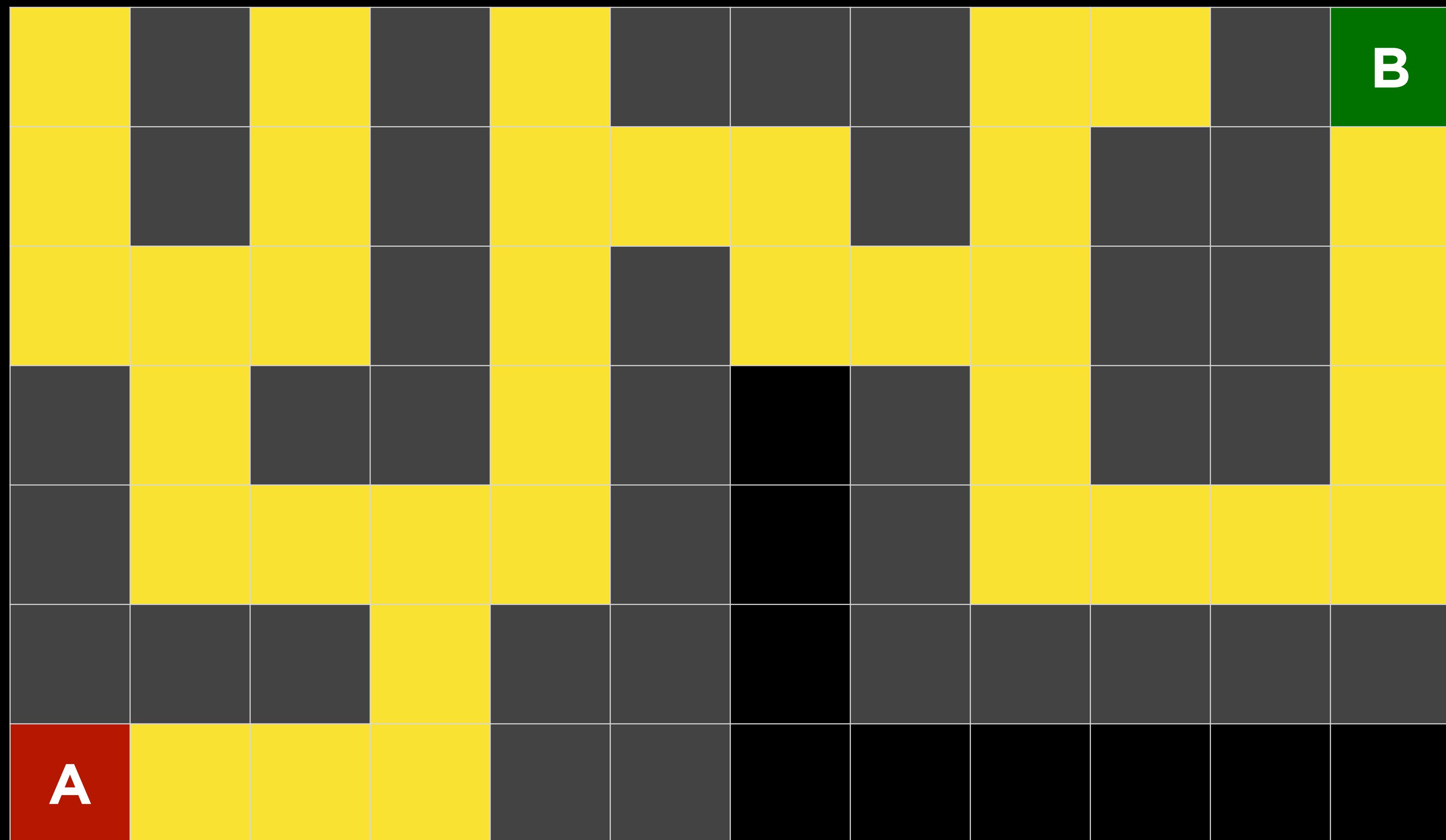
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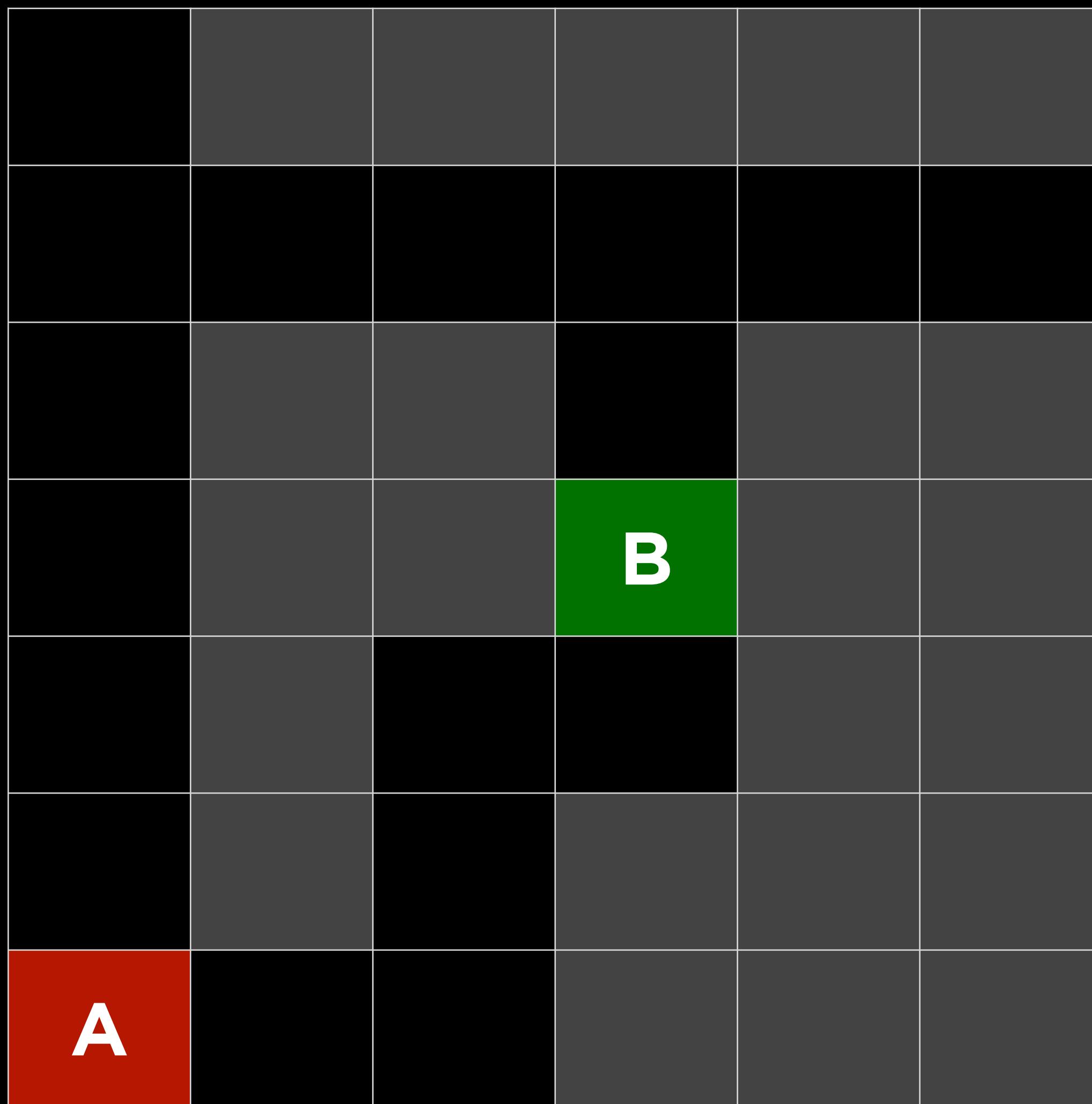
# Depth-First Search



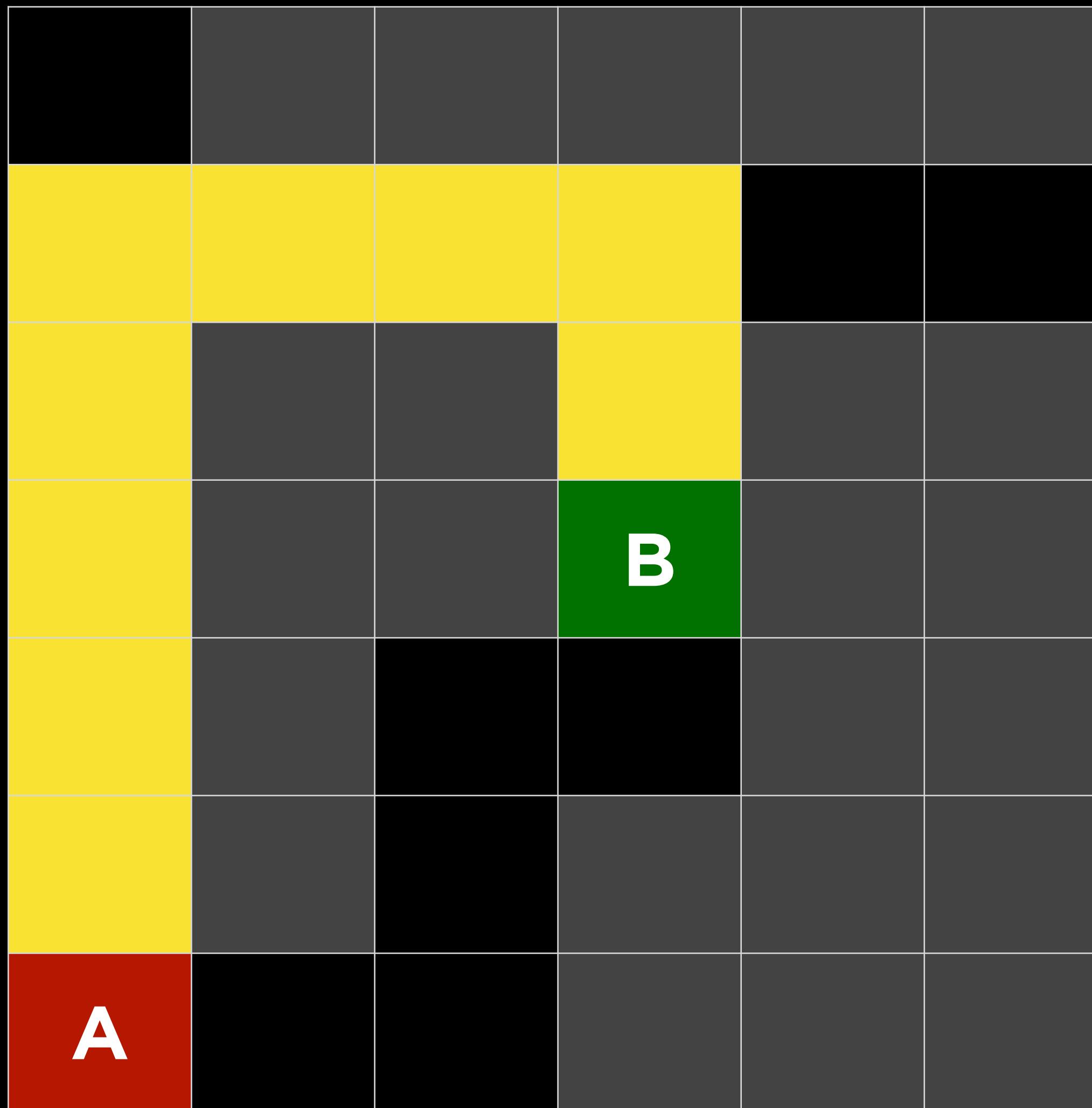
# Depth-First Search



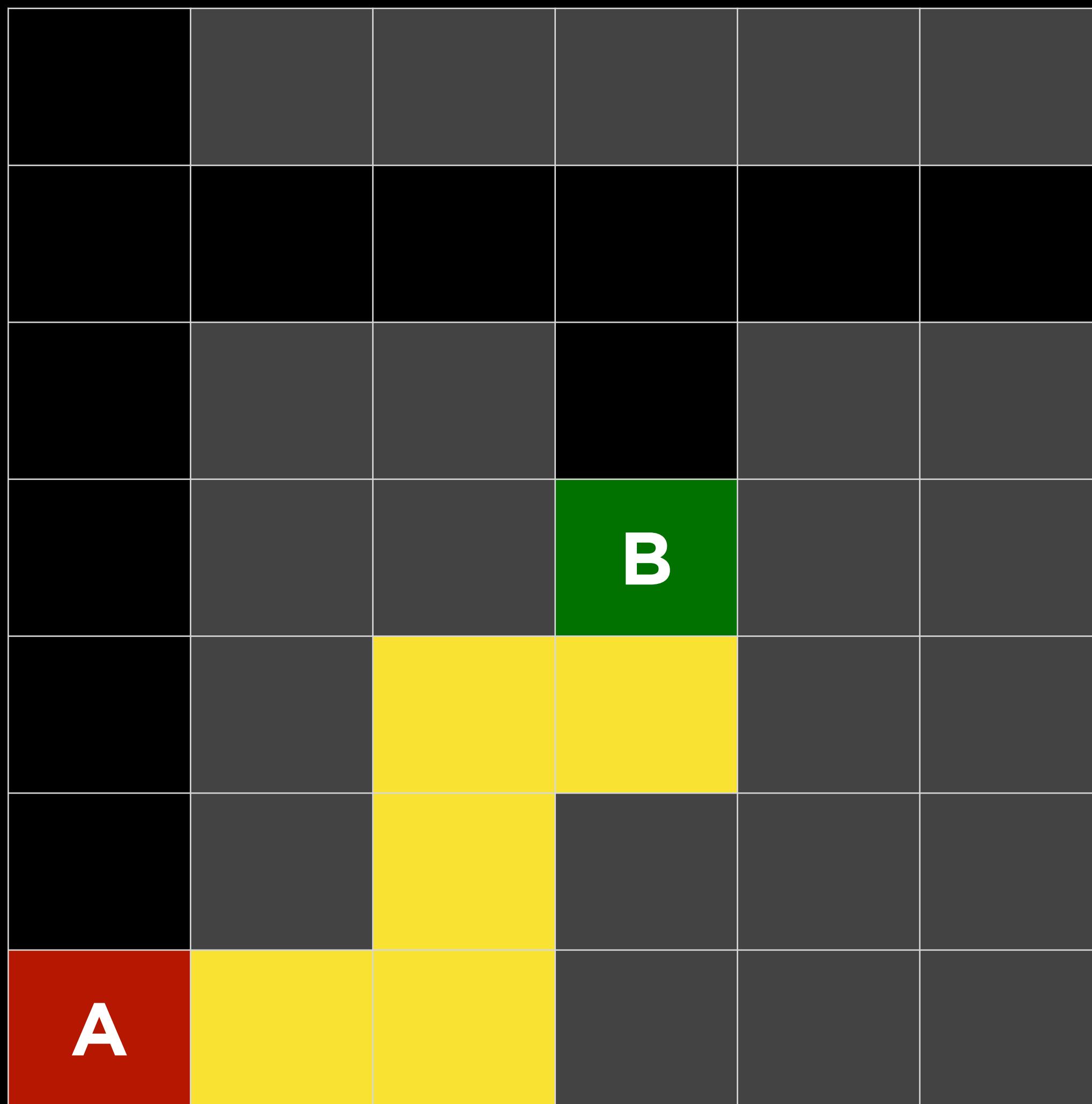
# Depth-First Search



# Depth-First Search

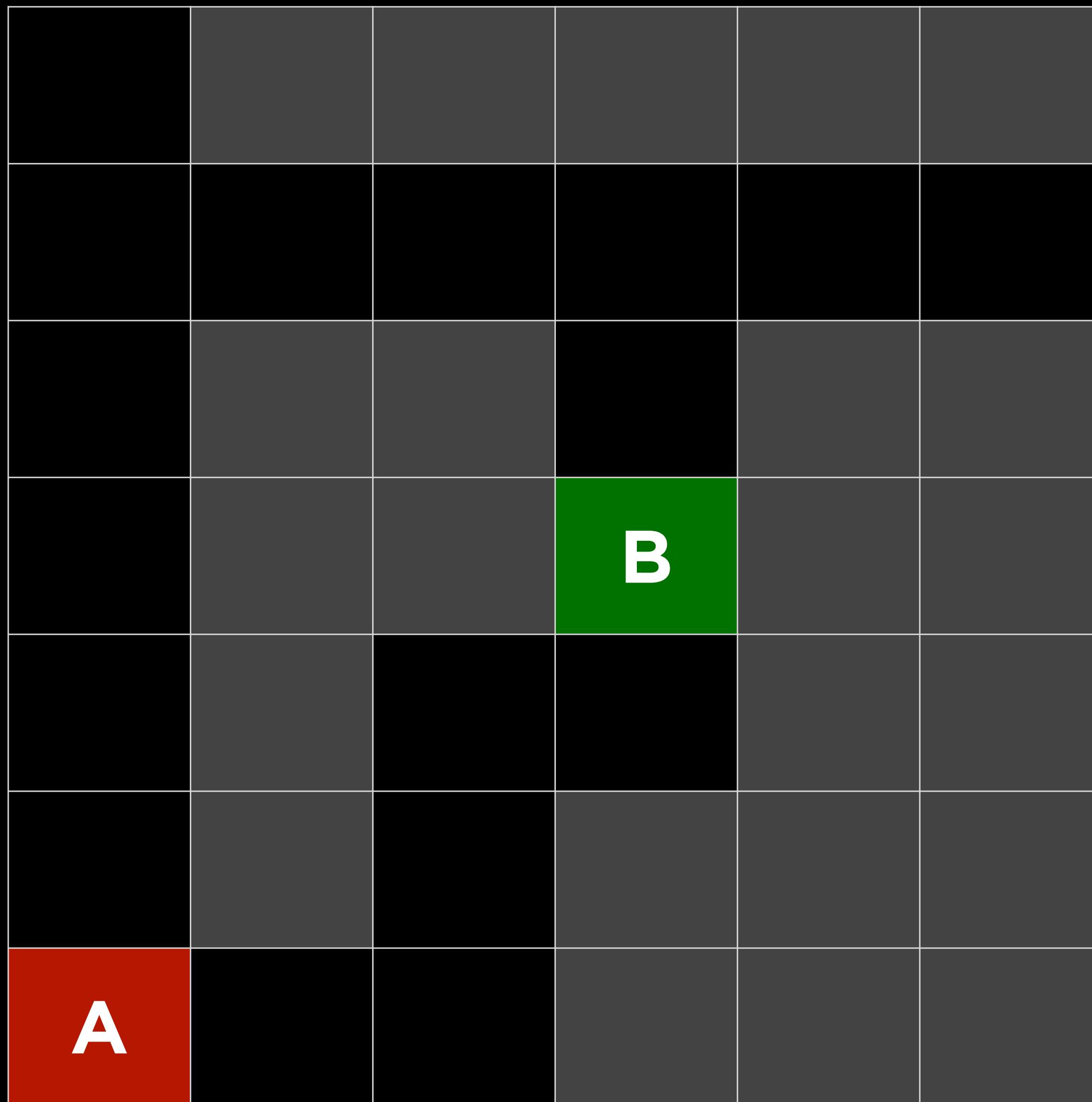


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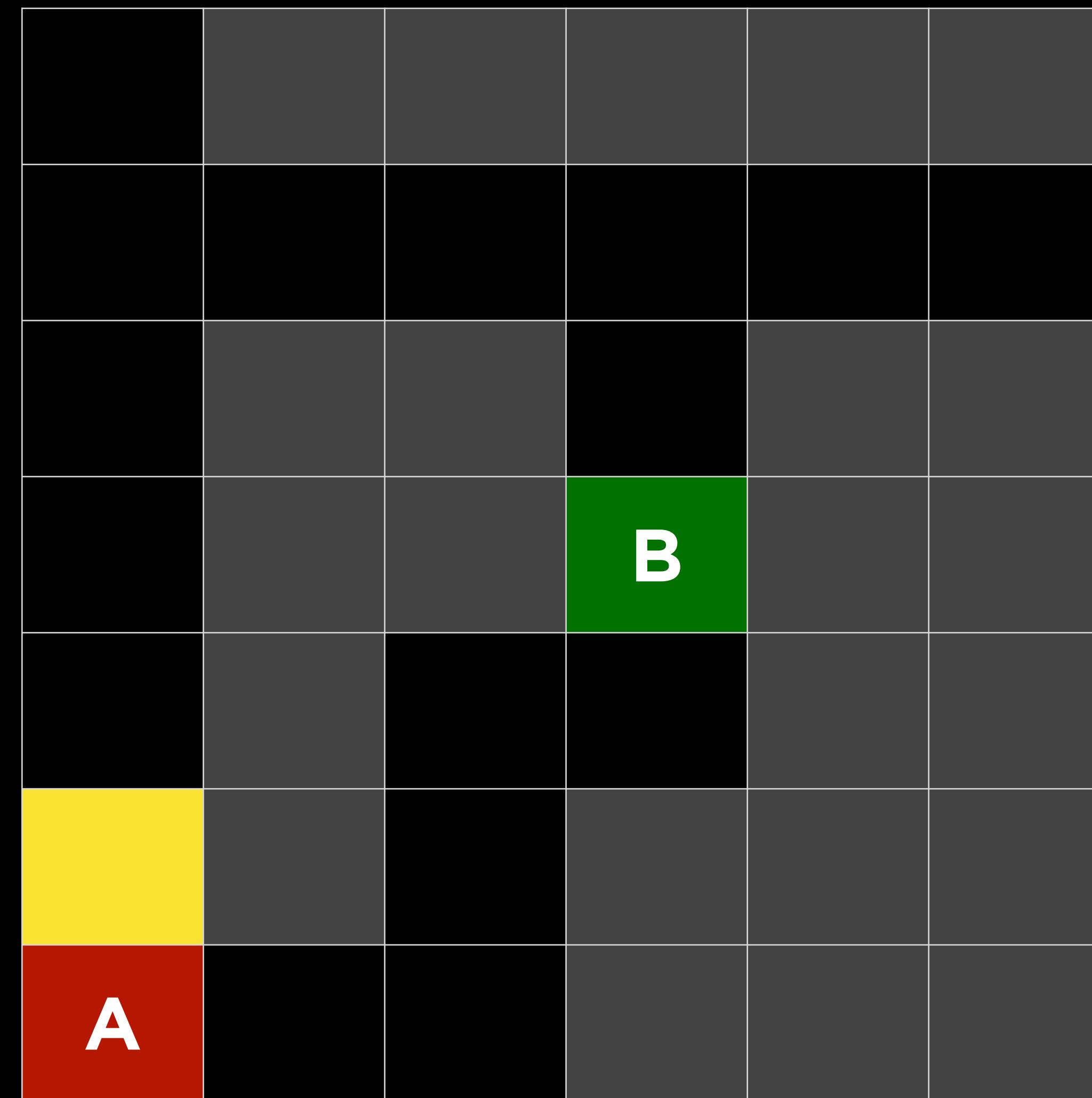


# Breadth-First Search

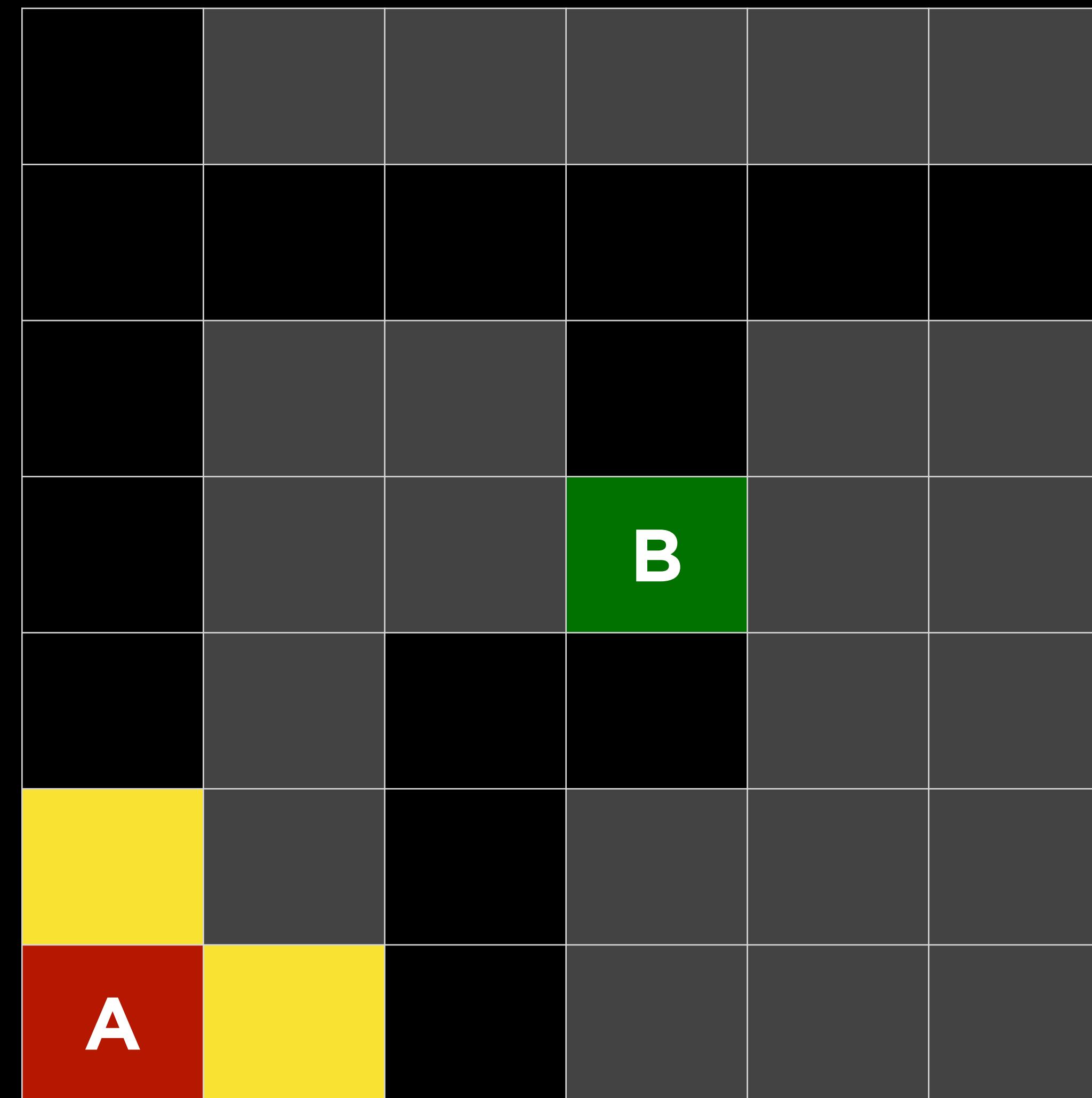
# Breadth-First Search



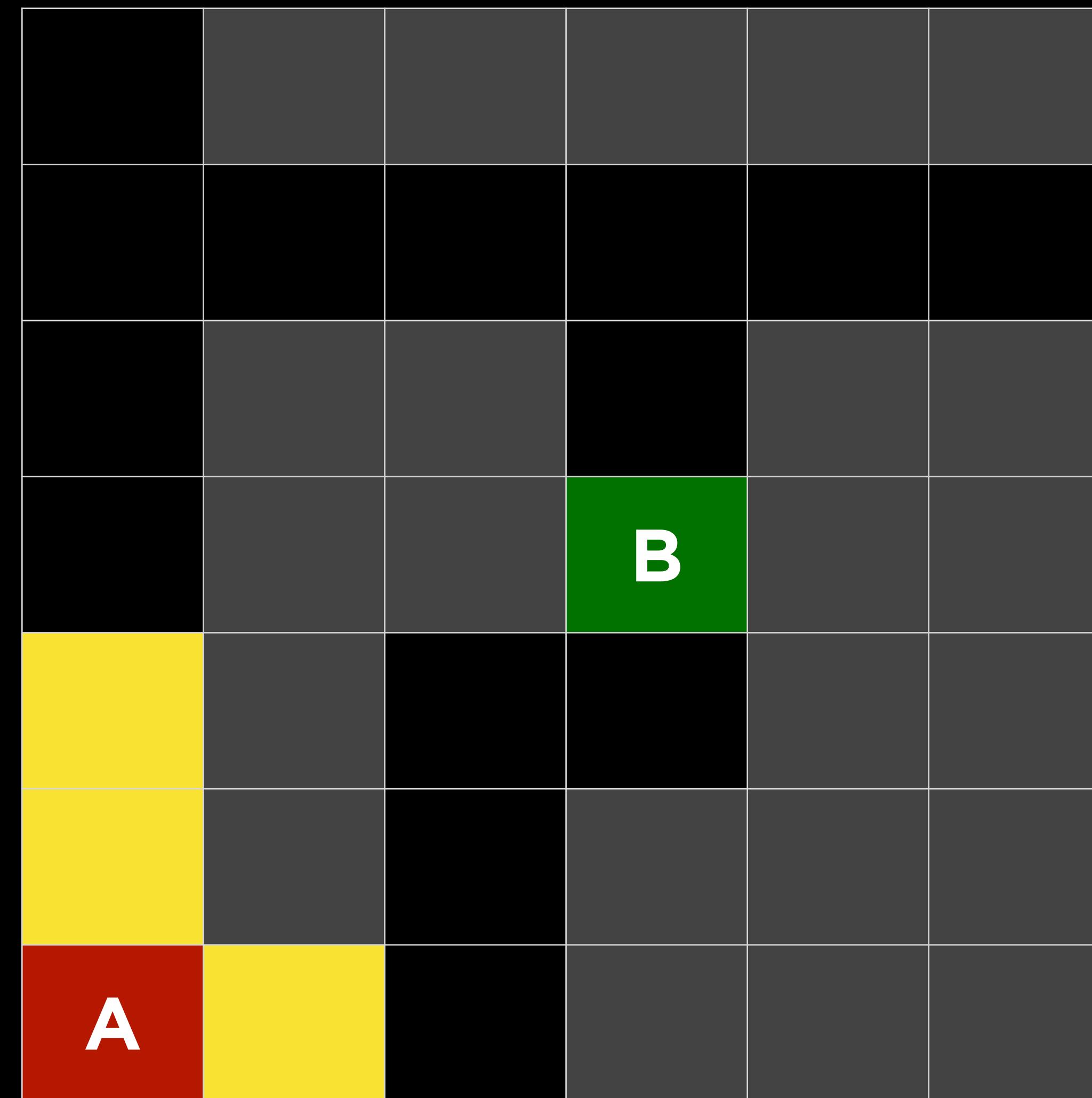
# Breadth-First Search



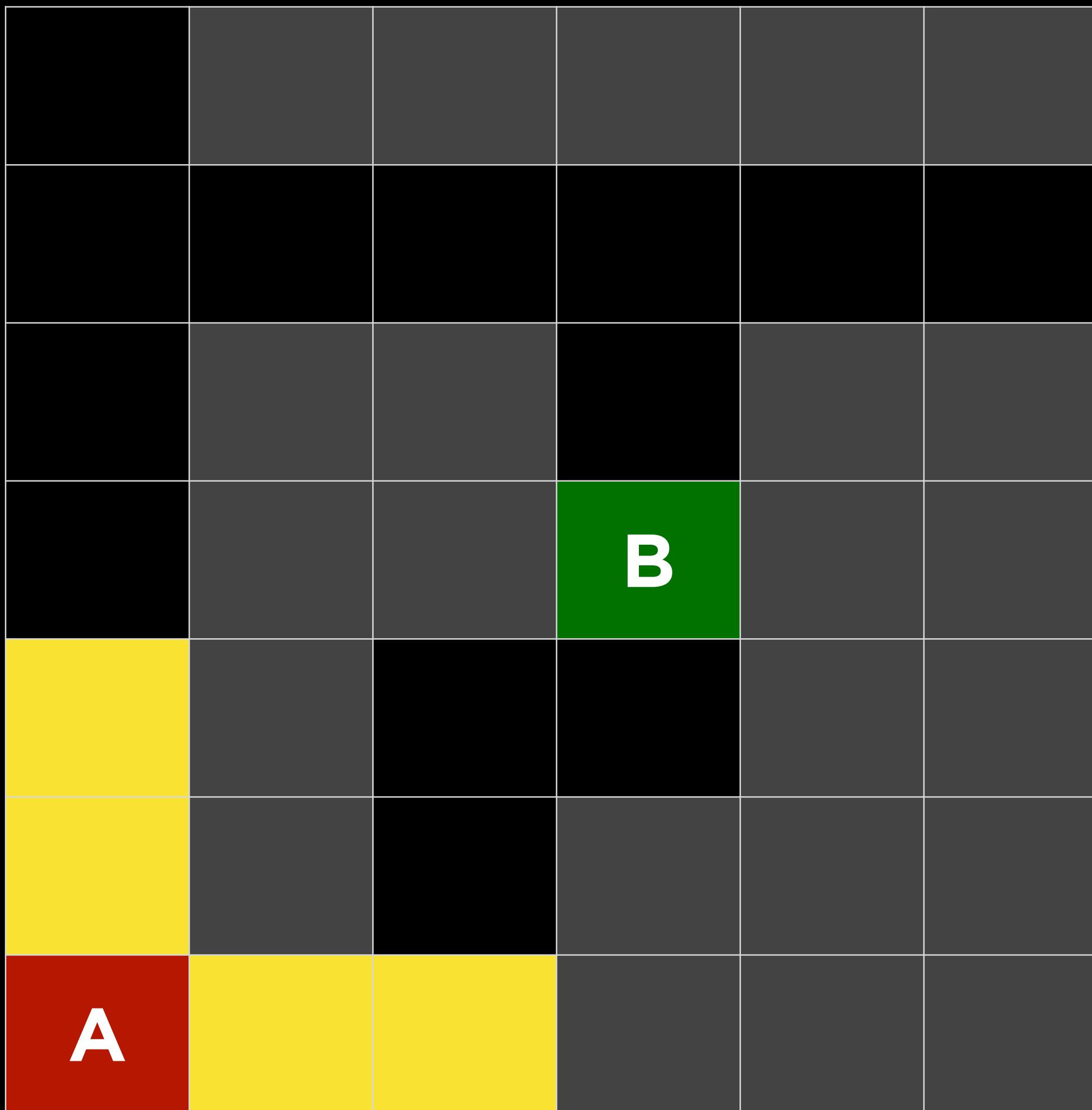
# Breadth-First Search



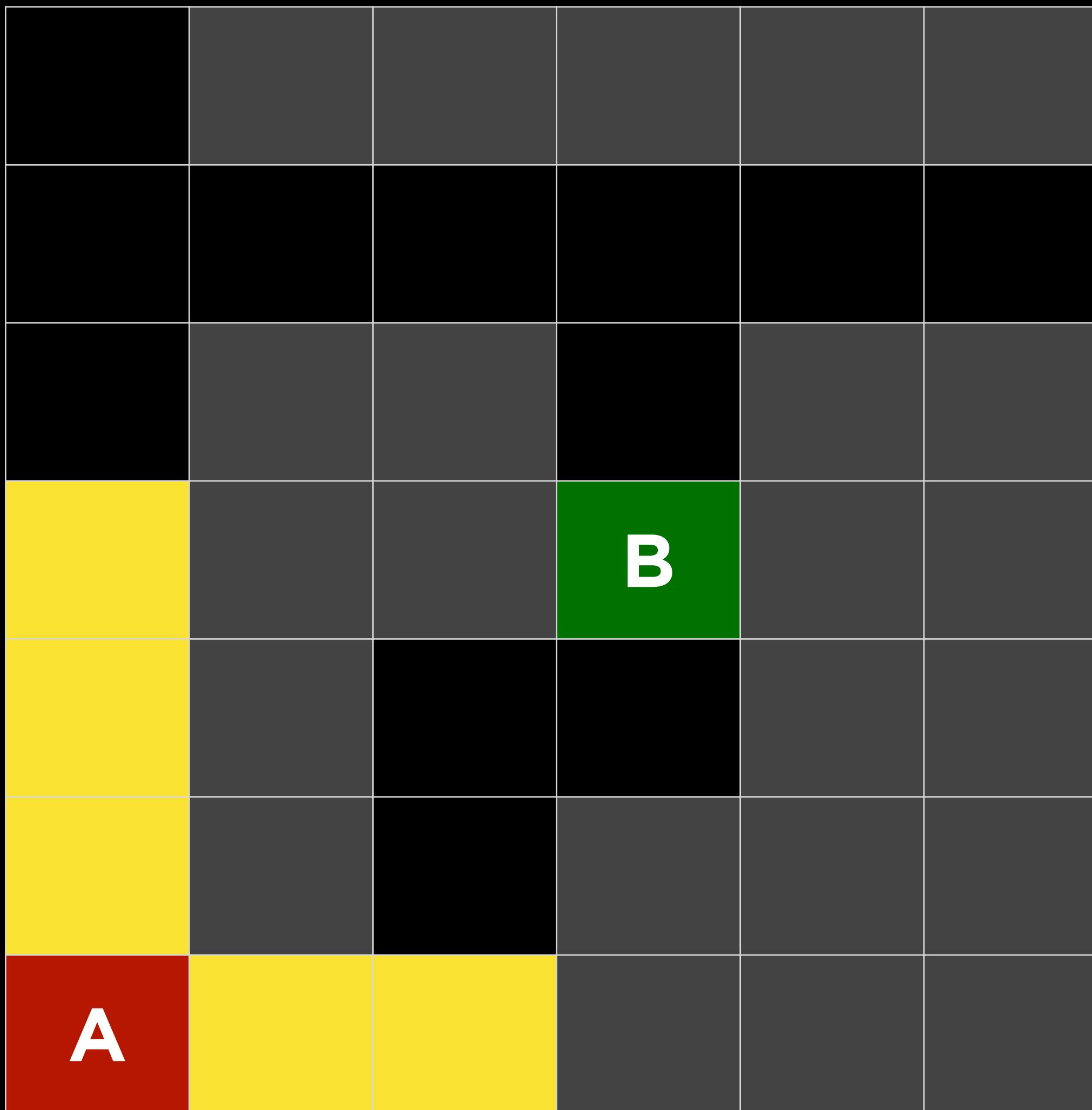
# Breadth-First Search



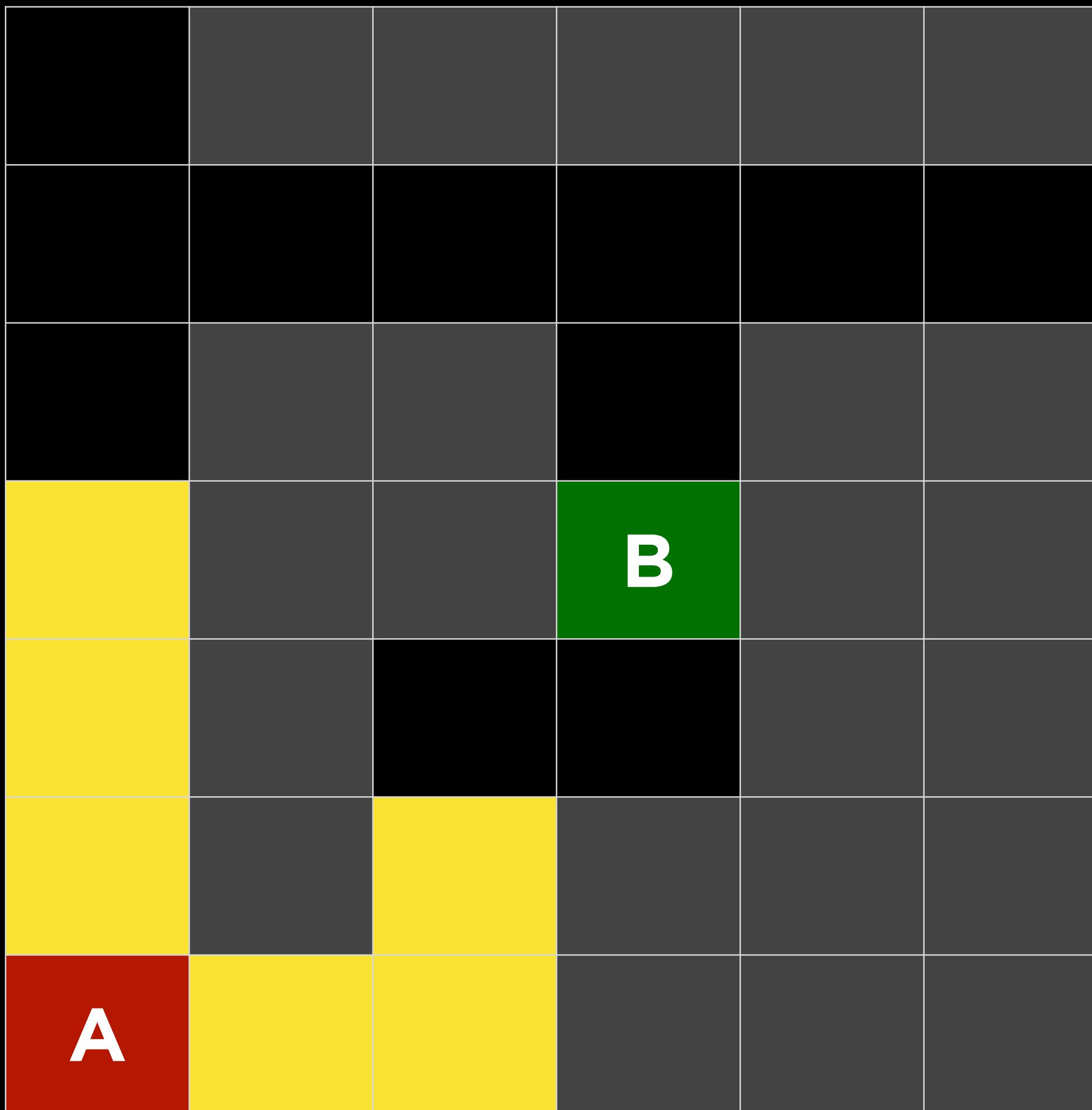
# Breadth-First Search



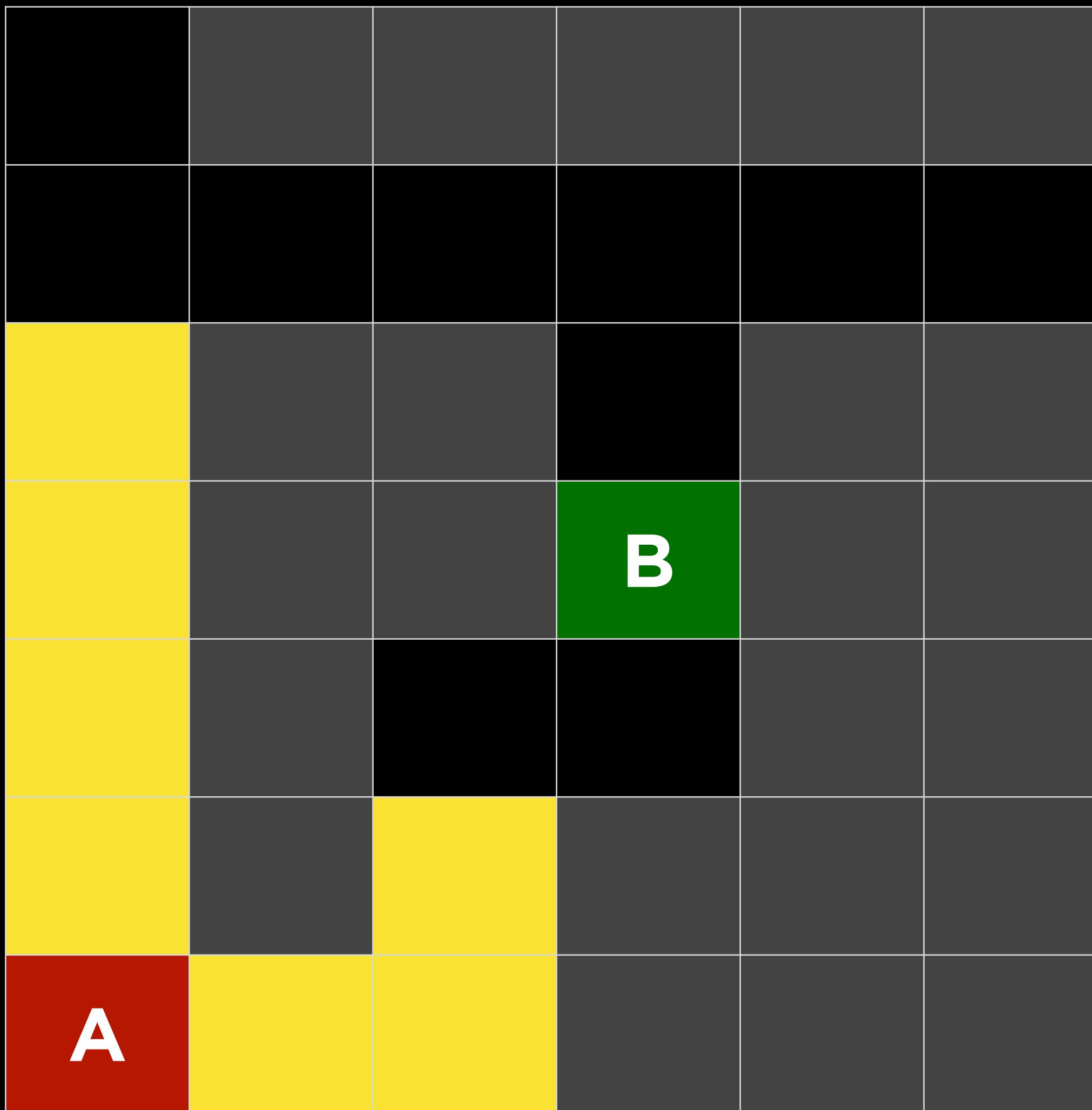
# Breadth-First Search



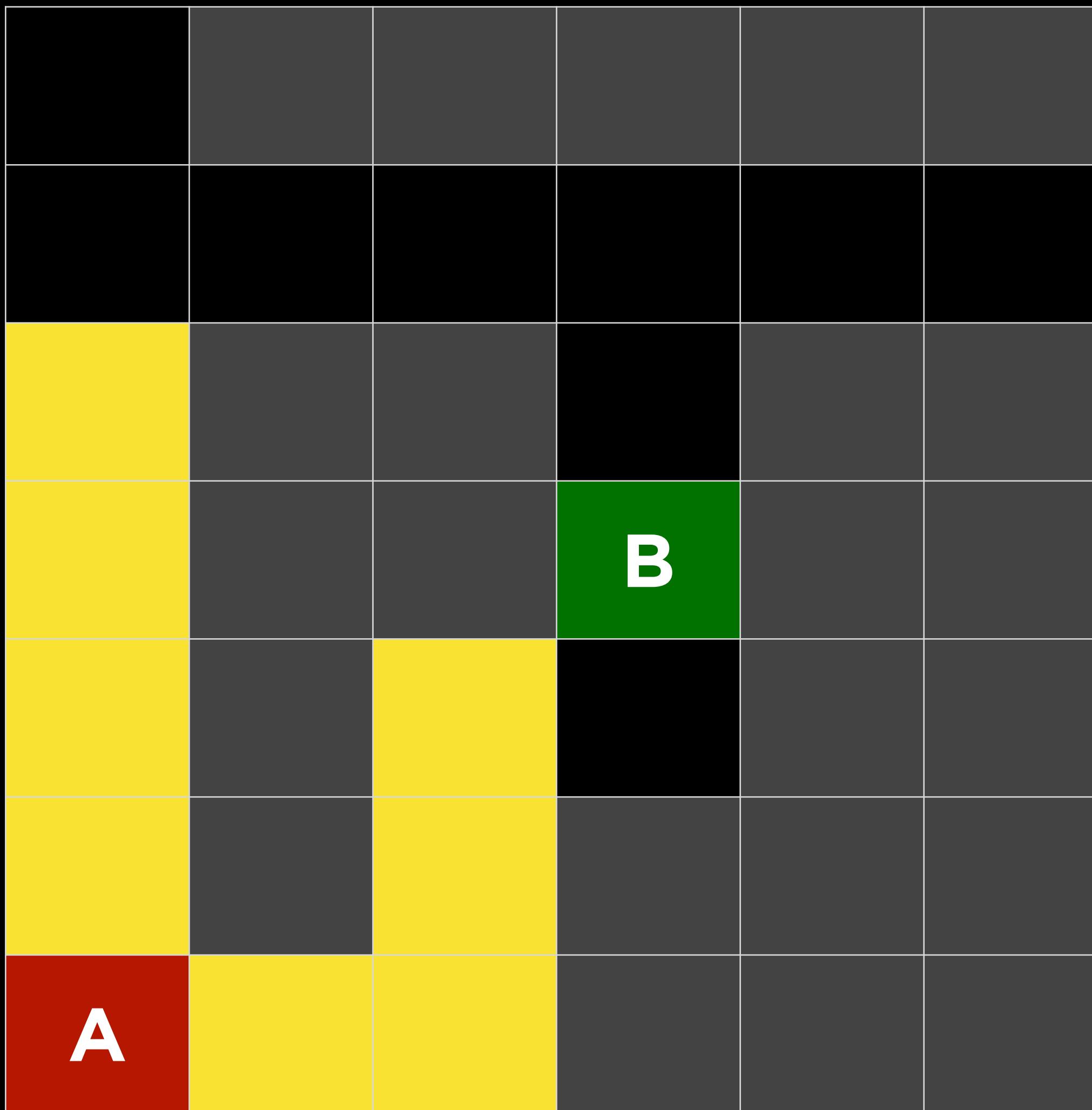
# Breadth-First Search



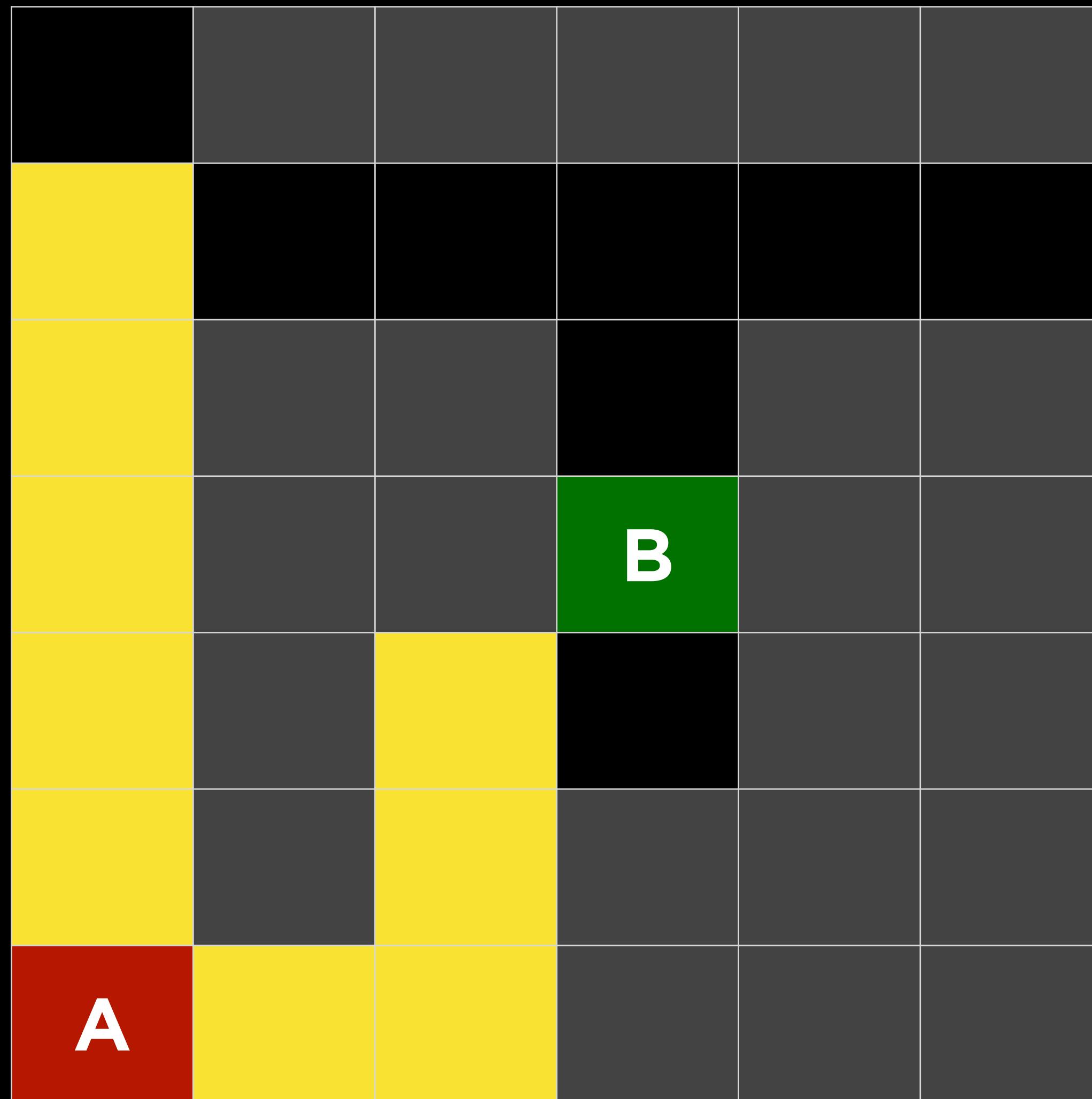
# Breadth-First Search



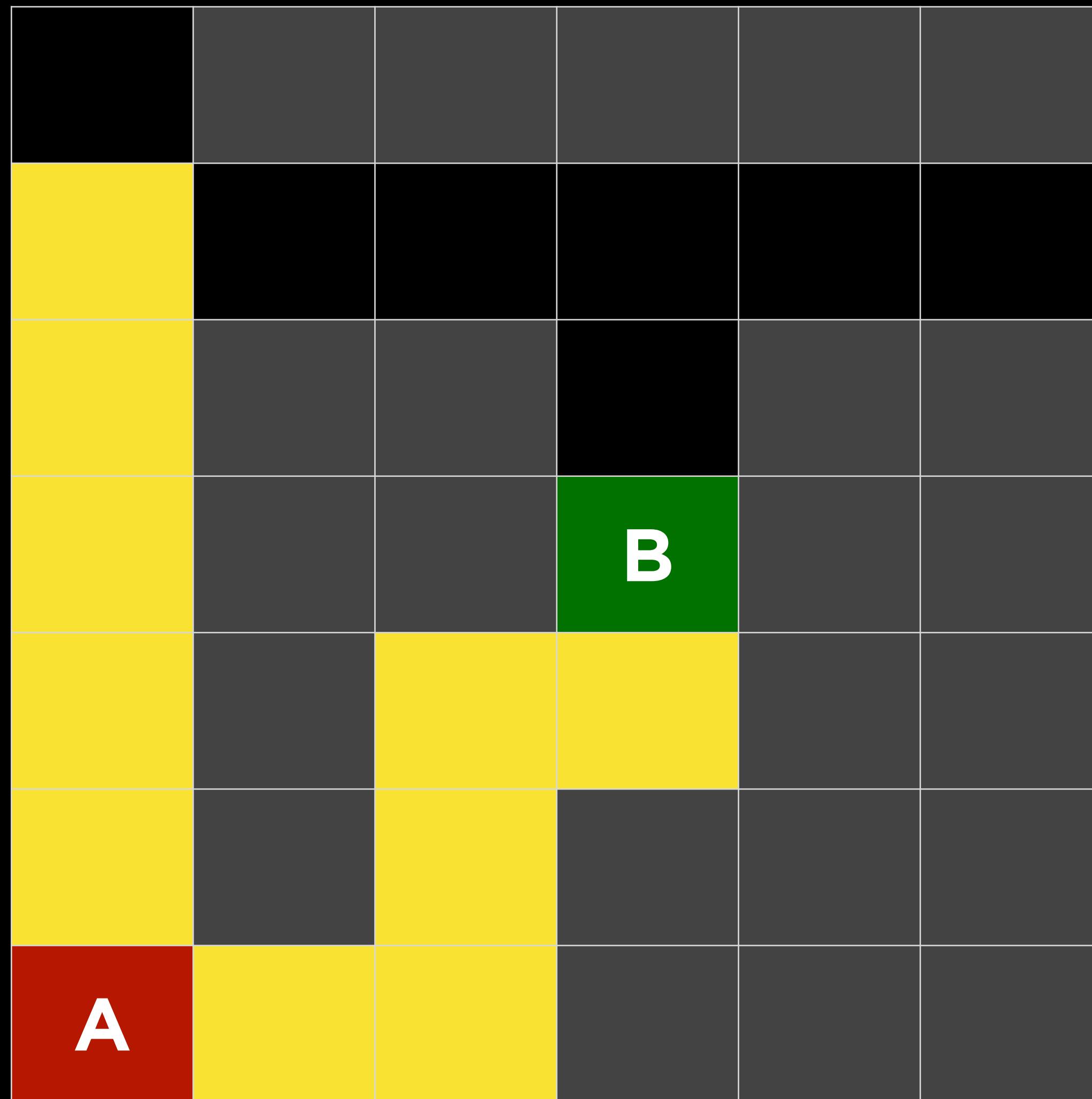
# Breadth-First Search



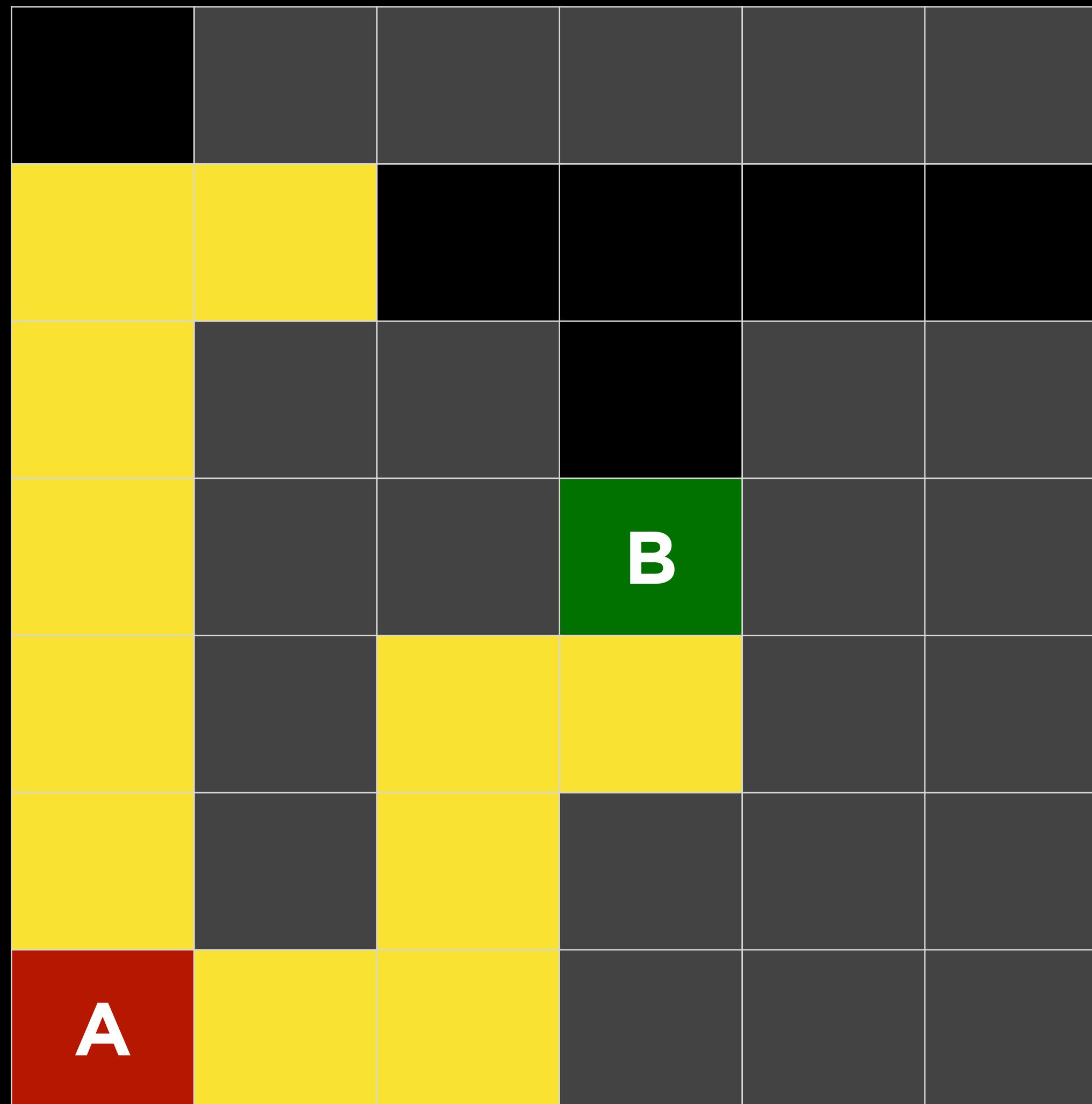
# Breadth-First Search



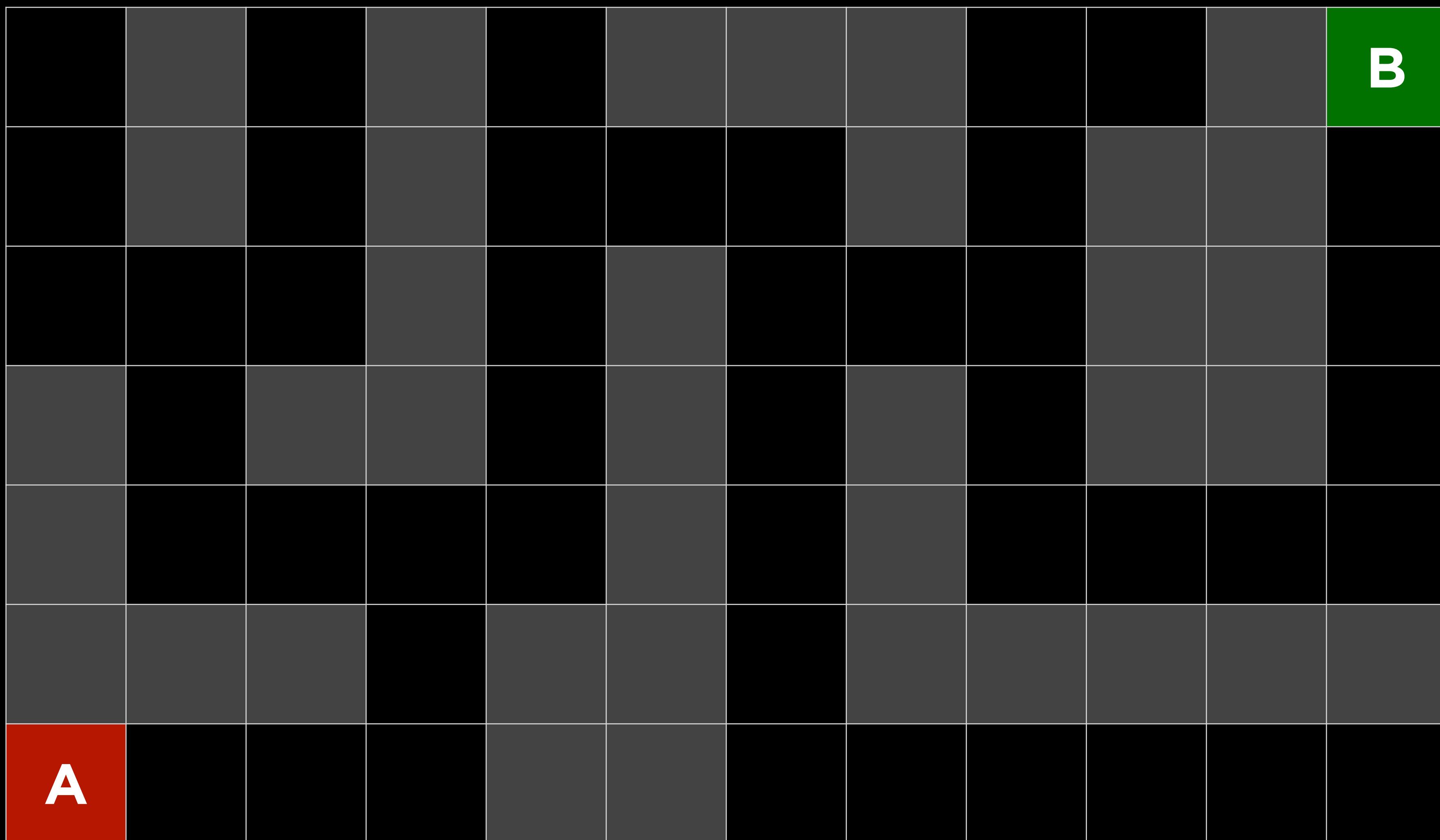
# Breadth-First Search



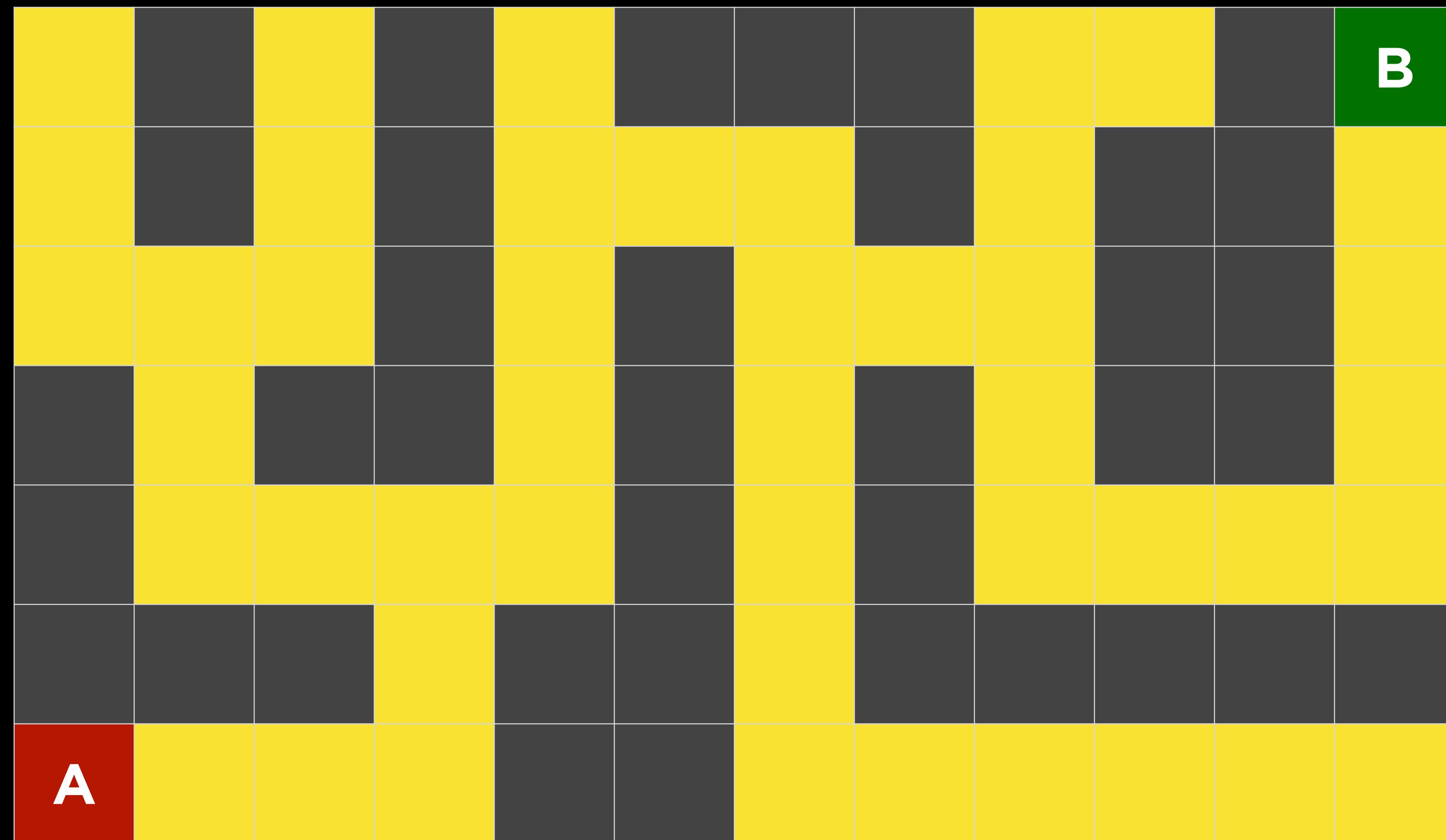
# Breadth-First Search



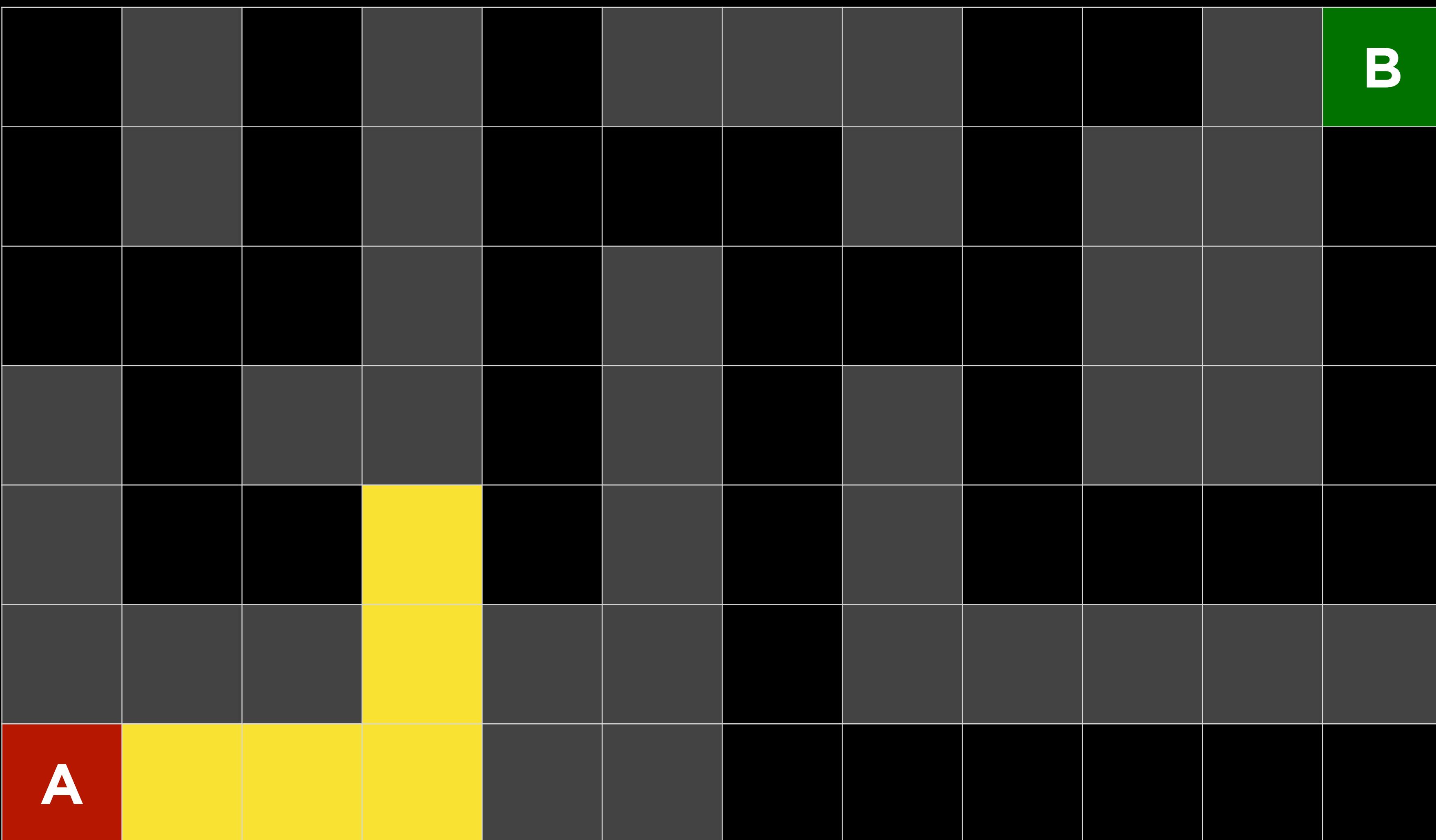
# Breadth-First Search



# Breadth-First Search



# Breadth-First Search

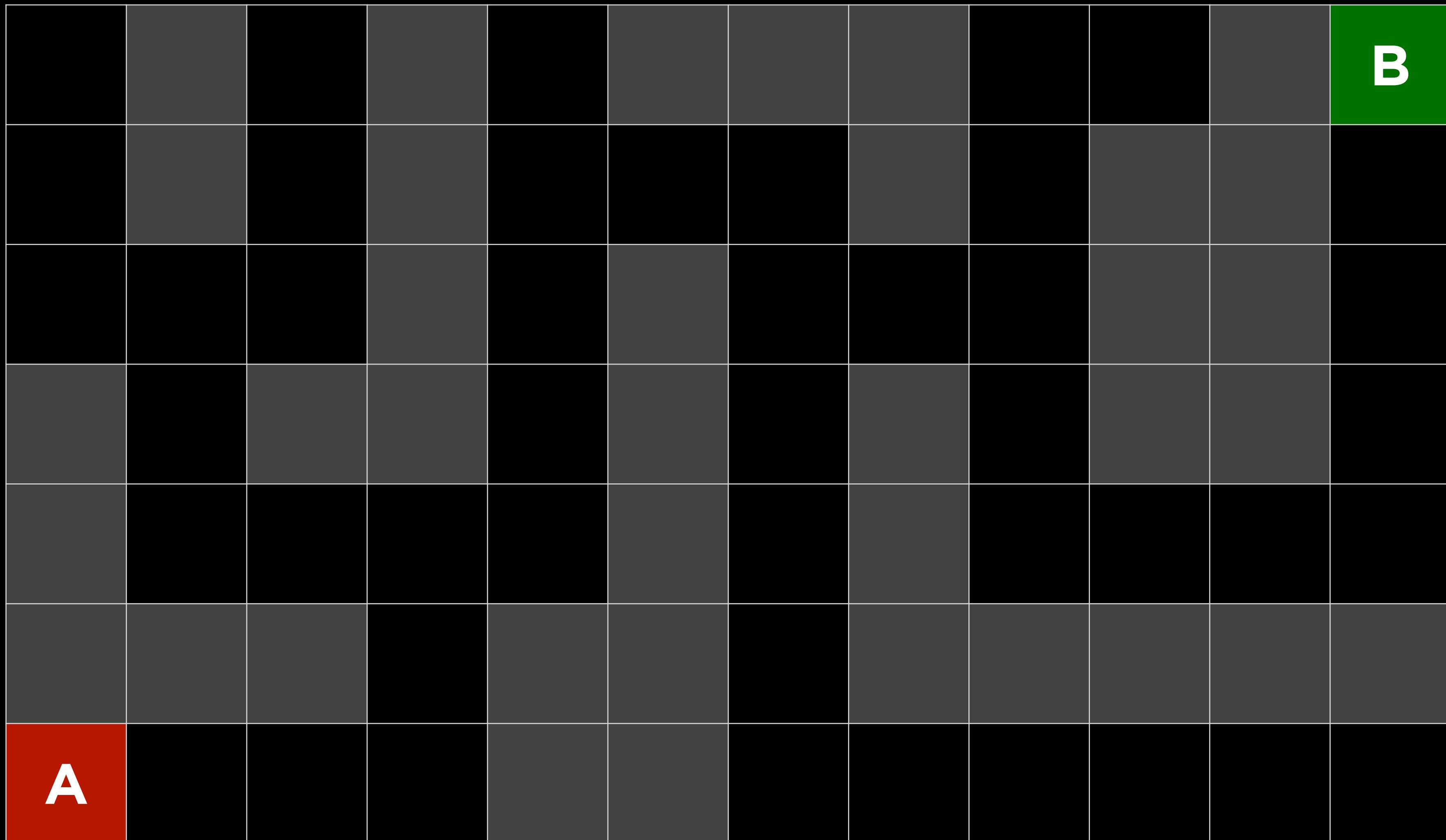


# uninformed search

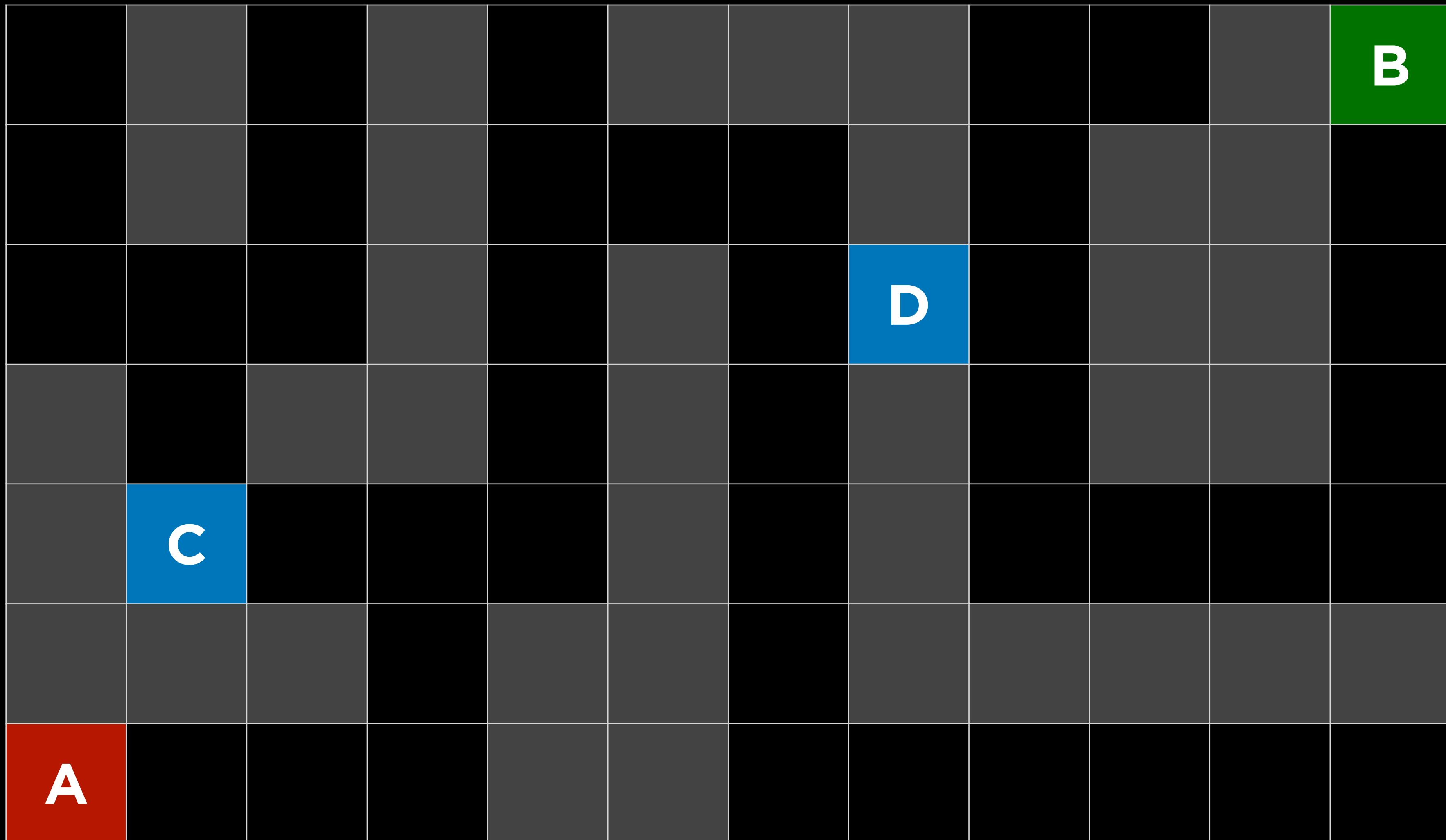
# informed search

search strategy that uses problem-specific knowledge to find solutions more efficiently

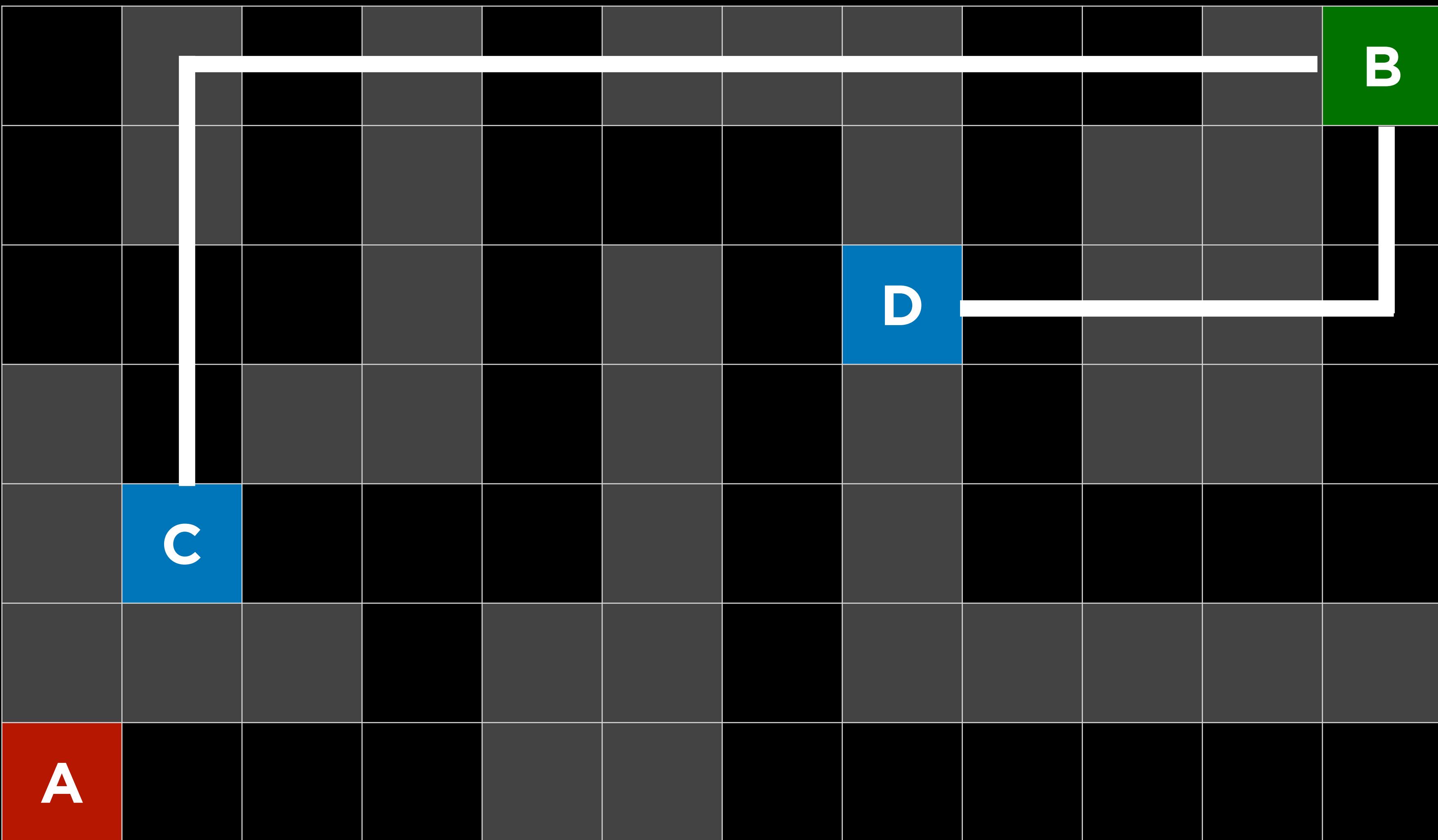
# Heuristic?



# Heuristic?



# Manhattan Distance



# Greedy Best-First Search

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B	
12		10		8	7	6		4			1	
13	12	11		9		7	6	5			2	
	13			10		8		6			3	
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14				11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13			10				
A	16	15	14				11	10	9	8	7

# Greedy Best-First Search

11		9		7				3	2		B	
12		10		8	7	6		4			1	
13	12	11		9		7	6	5			2	
	13			10		8		6			3	
	14	13	12	11		9		7	6	5	4	
			13			10						
A	16	15	14				11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B	
12		10		8	7	6		4			1	
13	12	11		9		7	6	5			2	
	13			10		8		6			3	
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14				11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

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11		9		7				3	2		B
12		10		8	7	6		4			1
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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
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# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
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# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7					3	2		B
12		10		8	7	6		4				1
13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14			11	10	9	8	7	6	

# Greedy Best-First Search

11		9		7					3	2		B
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13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14			11	10	9	8	7	6	

# Greedy Best-First Search

11		9		7					3	2		B
12		10		8	7	6		4				1
13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14				11	10	9	8	7	6

# Greedy Best-First Search

11		9		7					3	2		B
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13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14			11	10	9	8	7	6	

# Greedy Best-First Search

11		9		7					3	2		B
12		10		8	7	6		4				1
13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14			11	10	9	8	7	6	

# Greedy Best-First Search

11		9		7					3	2		B
12		10		8	7	6		4				1
13	12	11		9		7	6	5				2
	13			10		8		6				3
	14	13	12	11		9		7	6	5	4	
				13		10						
A	16	15	14			11	10	9	8	7	6	

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
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# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
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# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		B
12		10		8	7	6		4			1
13	12	11		9		7	6	5			2
	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
				13		10					
A	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	16	15	14		12	11	10	9	8	7	6

# Greedy Best-First Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11							5	3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	16	15	14		12	11	10	9	8	7	6

# Greedy Best-First Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
				13		11					5
A	16	15	14		12	11	10	9	8	7	6

# A\* Search

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	16	15	14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	1+16	15	14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	1+16	2+15	14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11						5		3
	14	13	12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		10	9	8	7	6	5	4		2
	13		6+11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	9	8	7	6	5	4		2
	13		6+11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	8	7	6	5	4		2
	13		6+11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	7	6	5	4		2
	13		6+11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	6	5	4		2
	13		6+11							5	3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	5	4		2
	13		6+11						5		3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	4		2
	13		6+11						5		3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	13		6+11						5		3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	13		6+11						14+5		3
	14	13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	13		6+11						14+5		3
	14	6+13	5+12		10	9	8	7	6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	13		6+11						14+5		3
	14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	12			7+10	8+9	9+8	10+7	11+6	12+5	13+4	2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	9	8	7	6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	8	7	6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	7	6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
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	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	14+7	6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	14+7	15+6	5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	14+7	15+6	16+5	4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	14+7	15+6	16+5	17+4	3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
			4+13		11						5
A	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

	11+10	12+9	13+8	14+7	15+6	16+5	17+4	18+3	2	1	B
	10+11										1
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		2
	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
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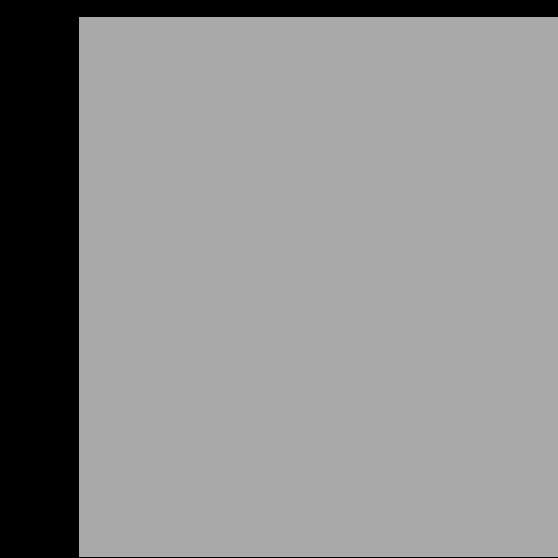
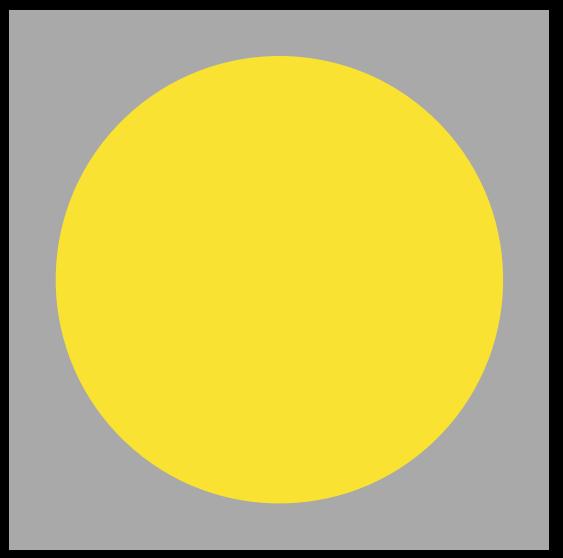
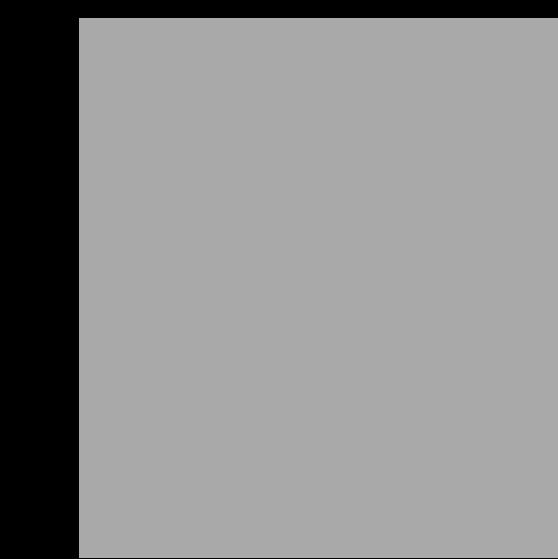
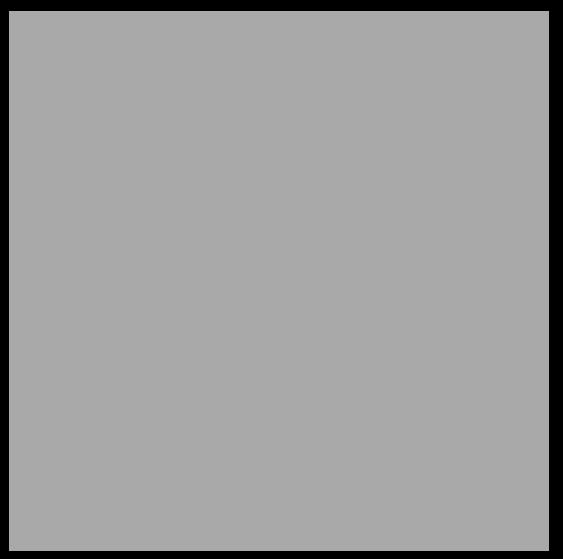
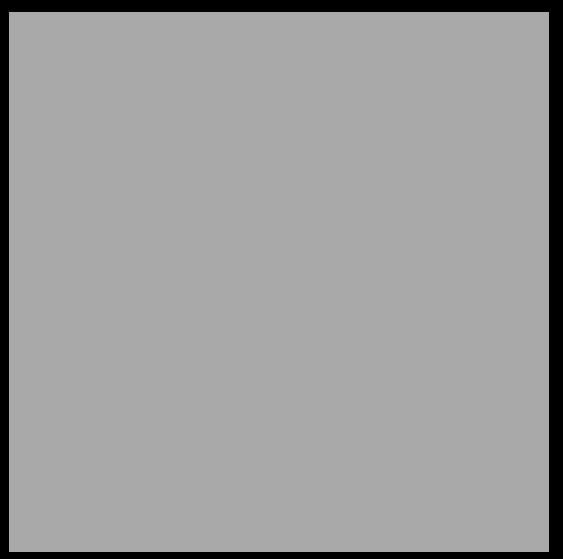
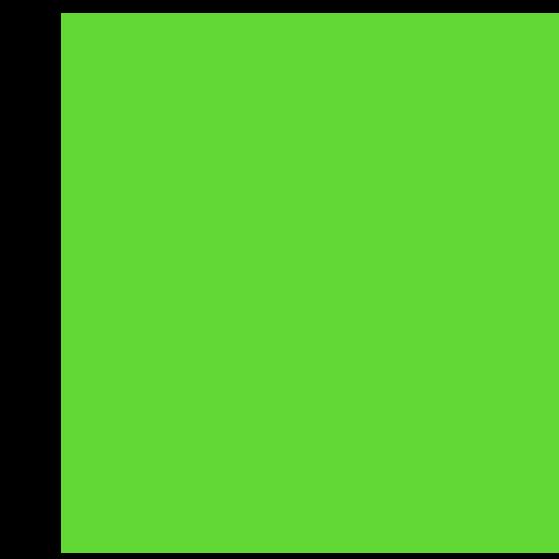
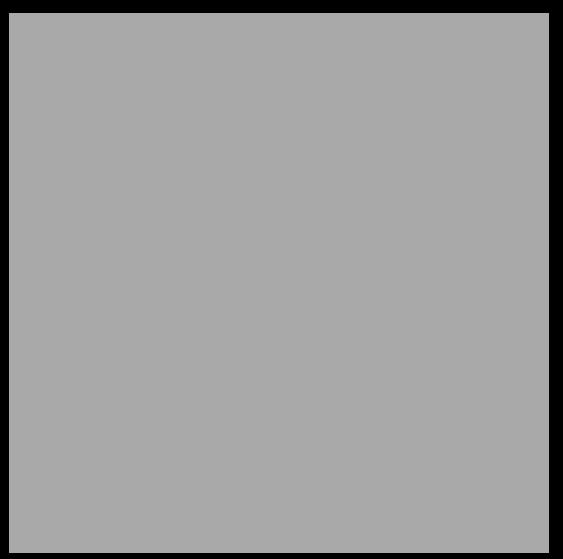
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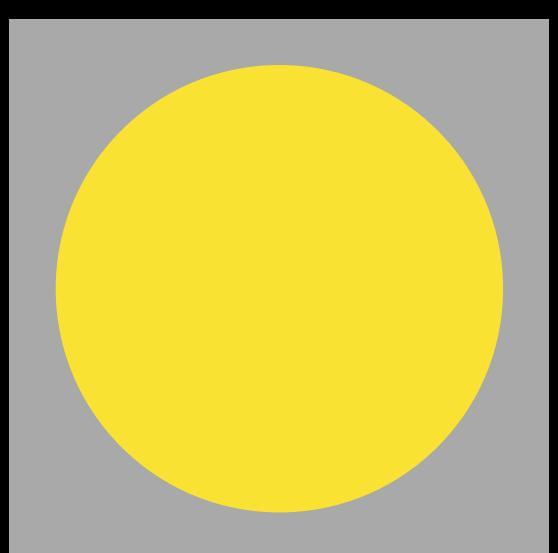
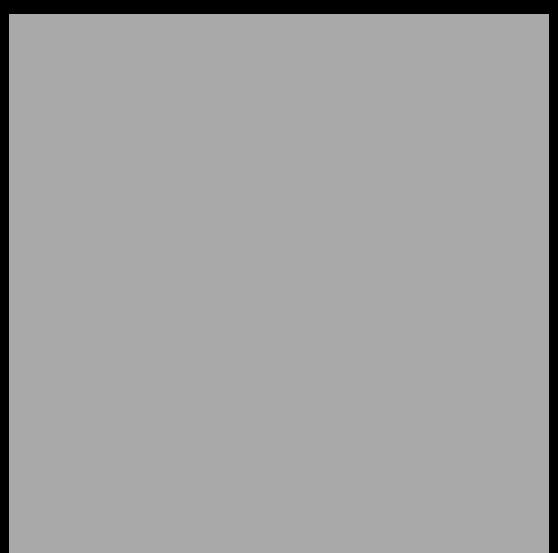
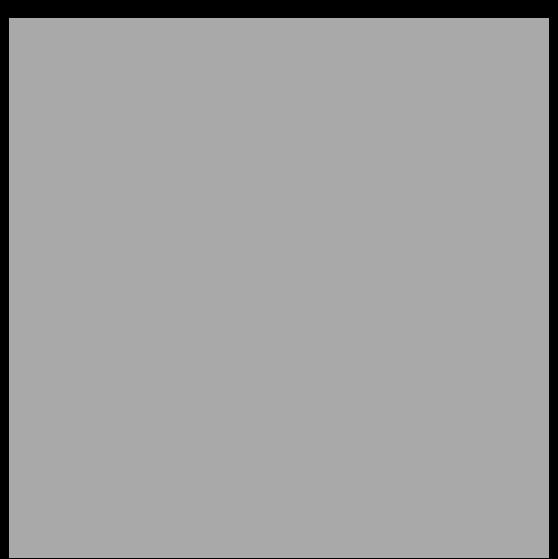
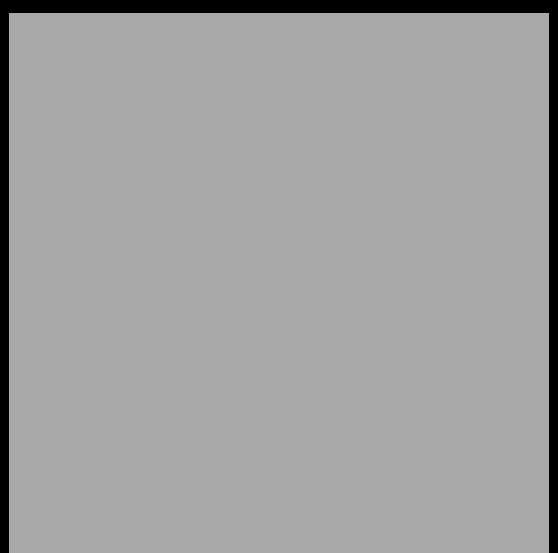
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	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
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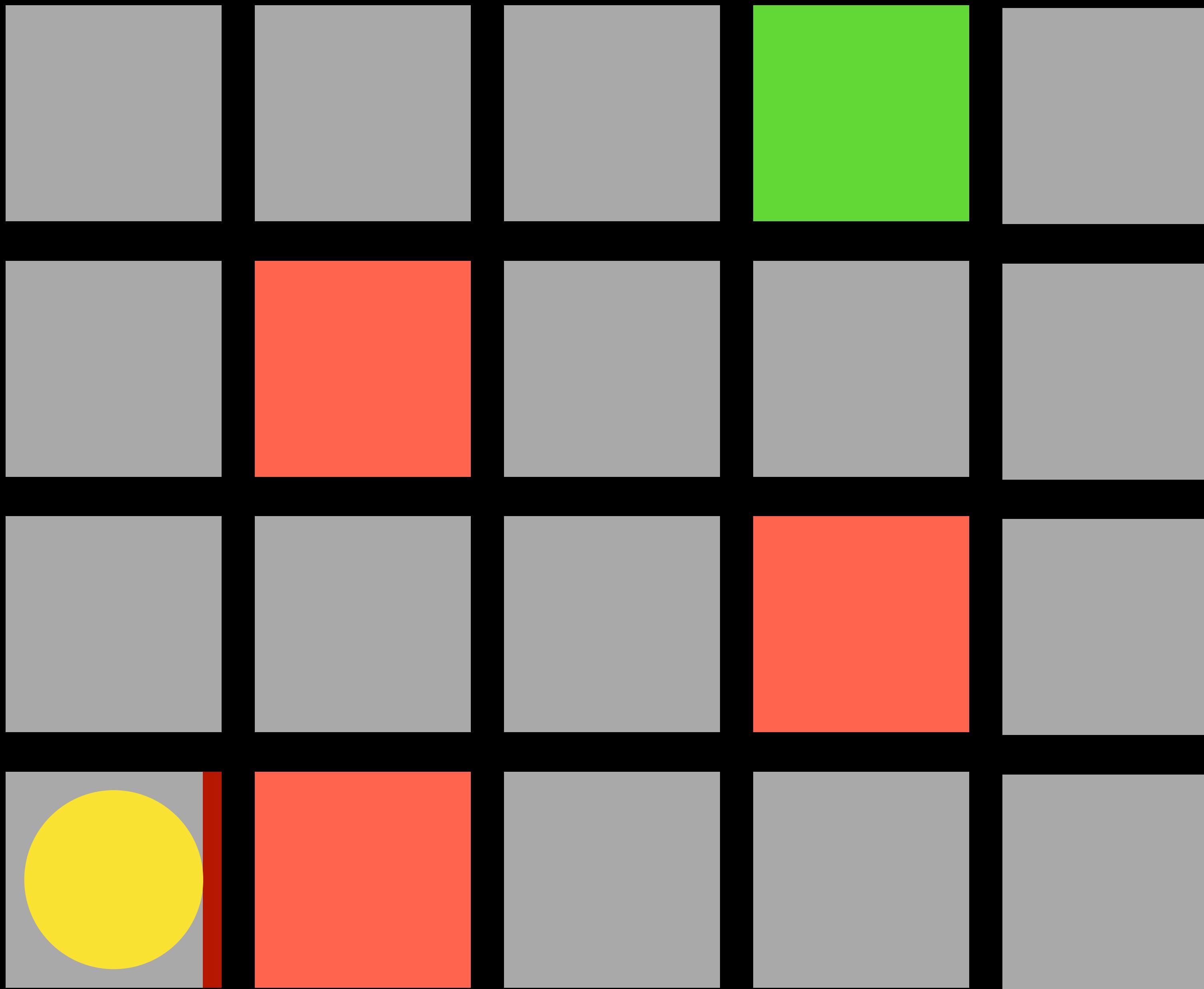
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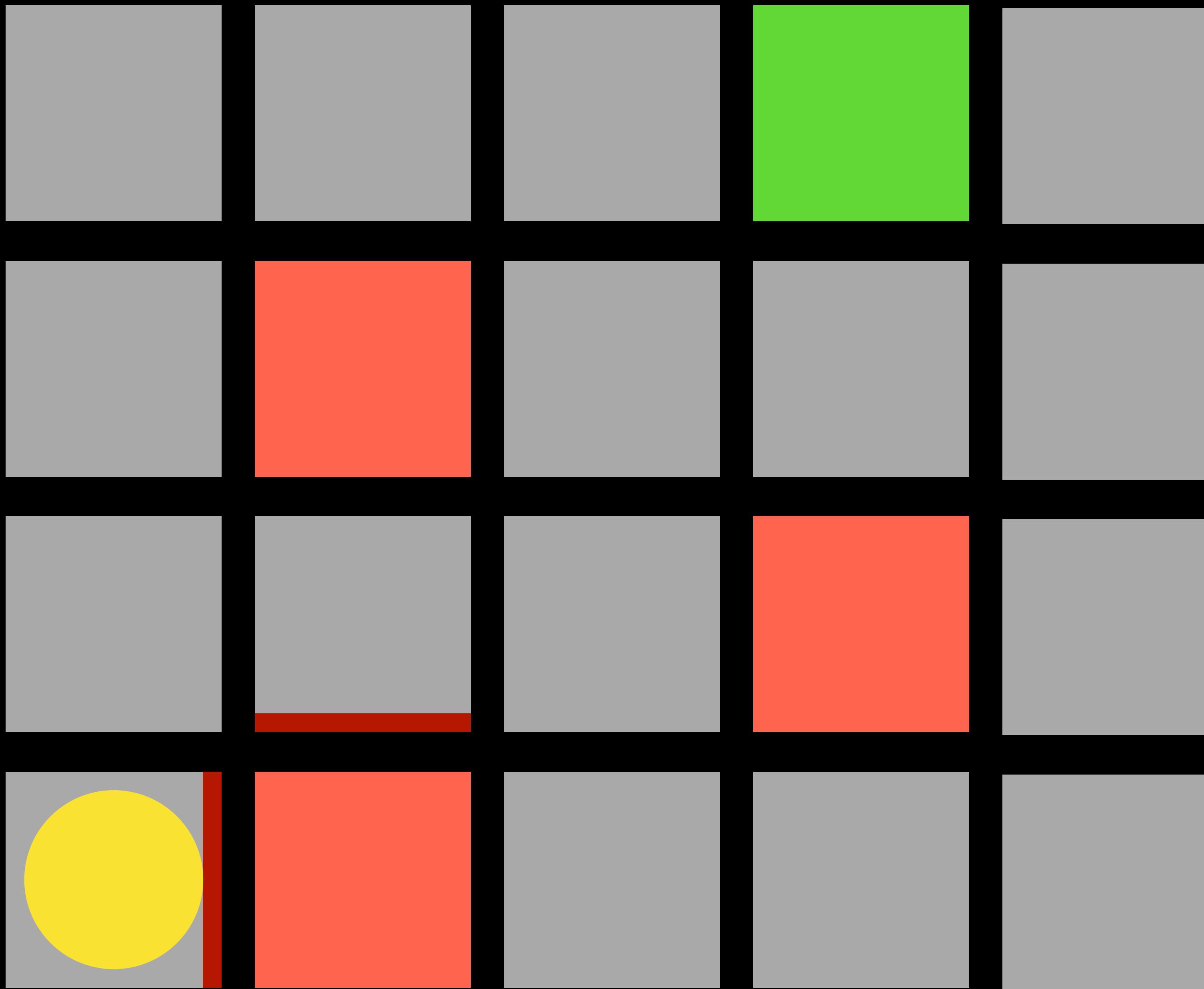
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	8+13		6+11						14+5		3
	7+14	6+13	5+12		10	9	8	7	15+6		4
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A	1+16	2+15	3+14		12	11	10	9	8	7	6

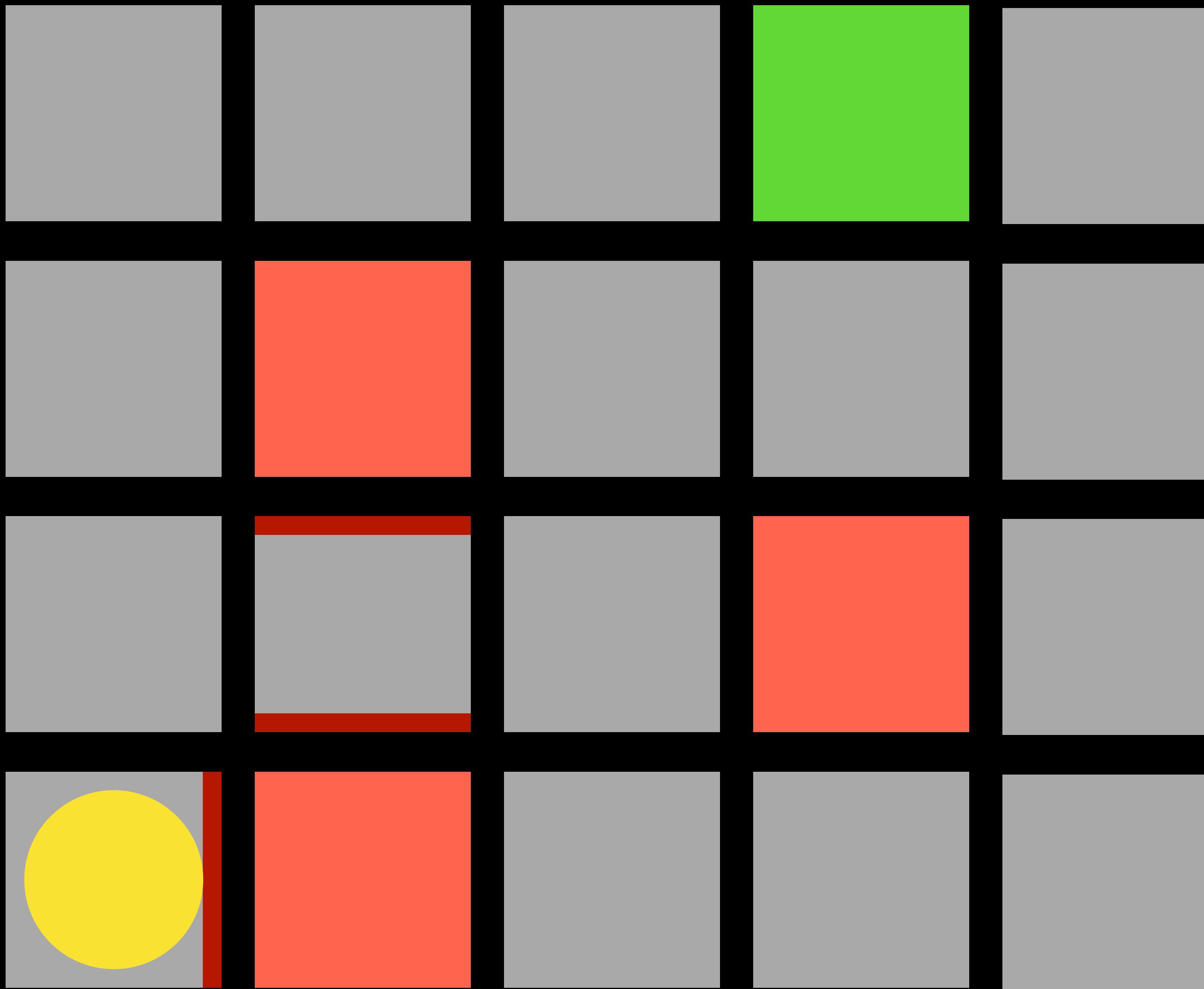
# Reinforcement Learning

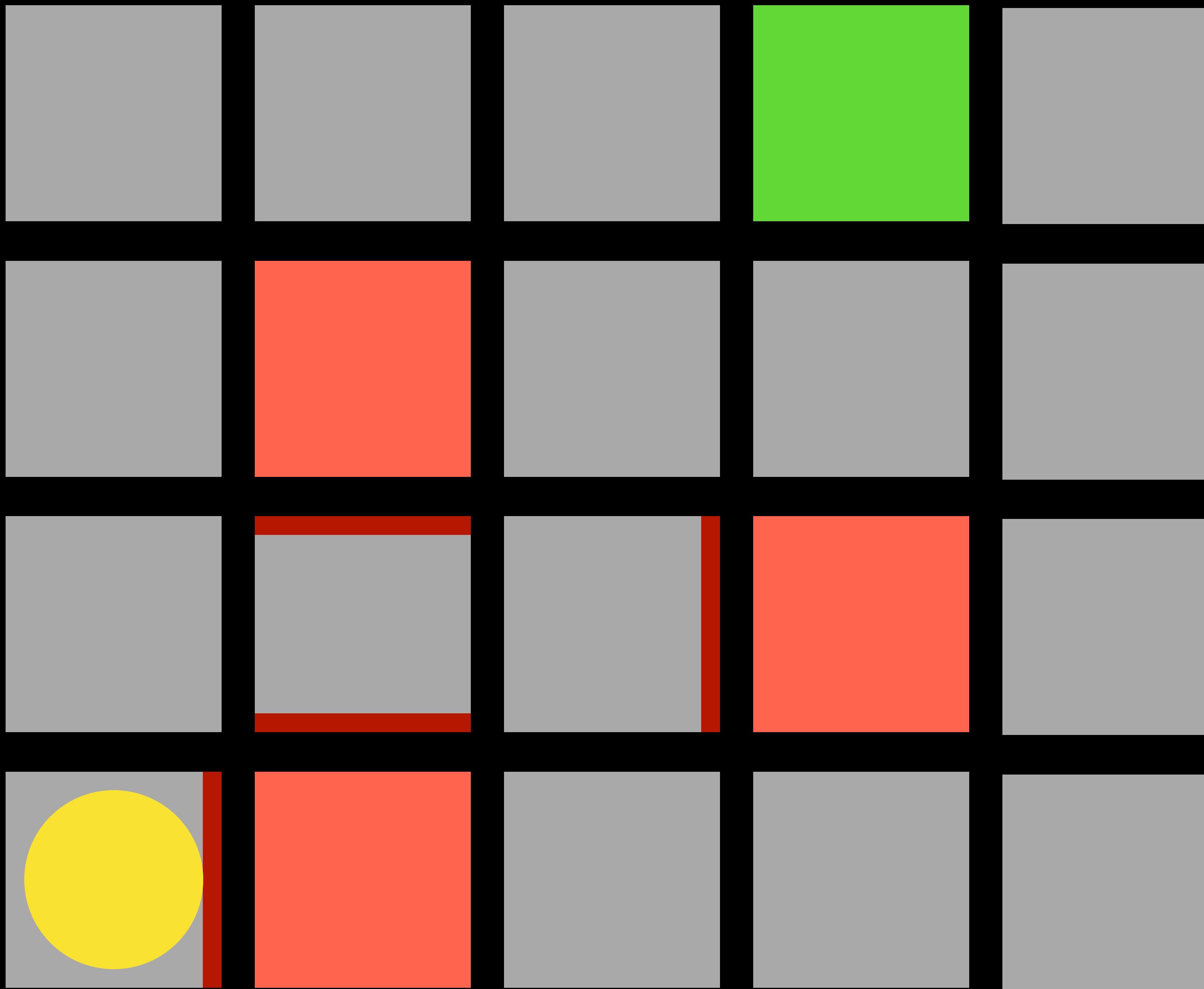


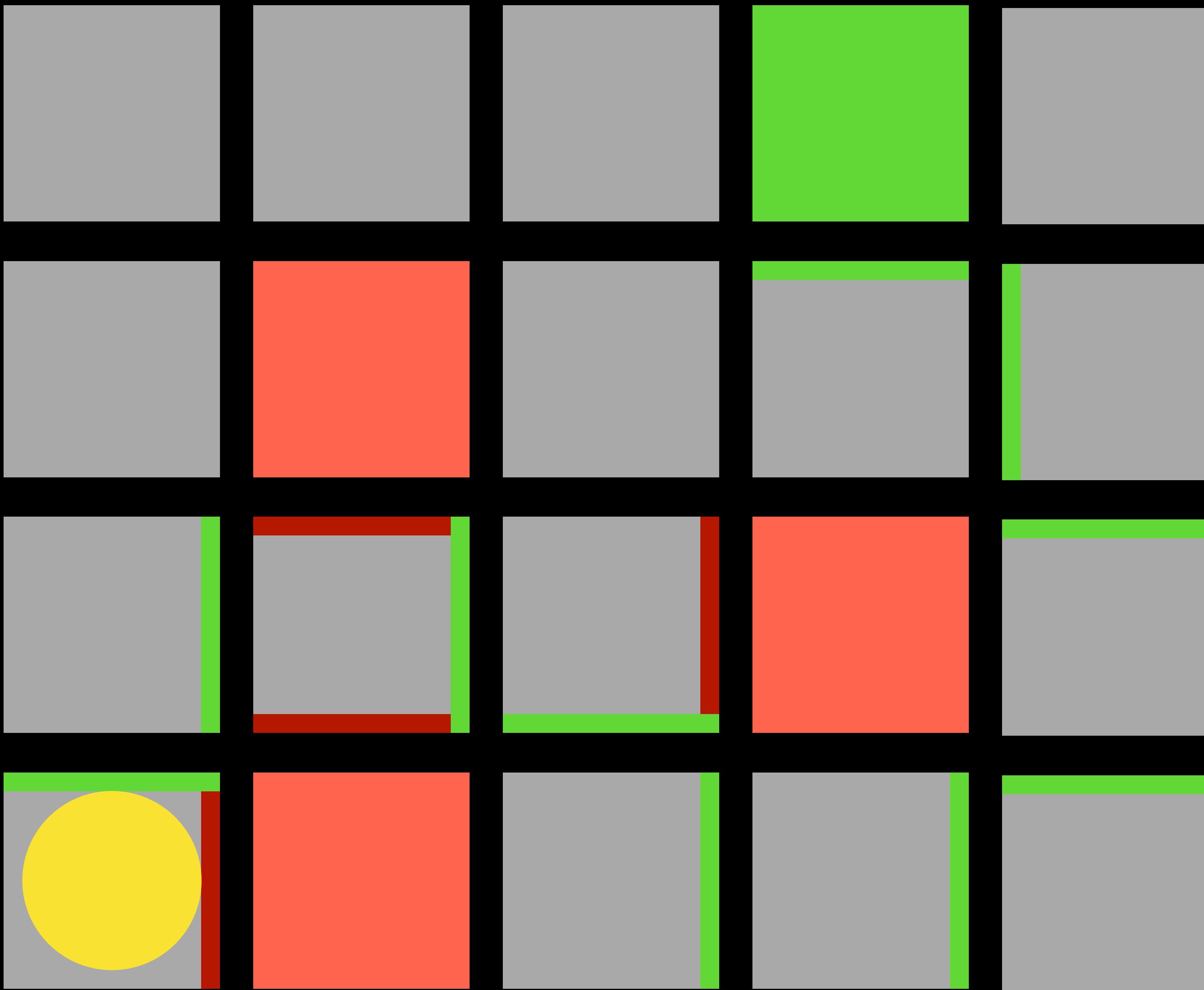


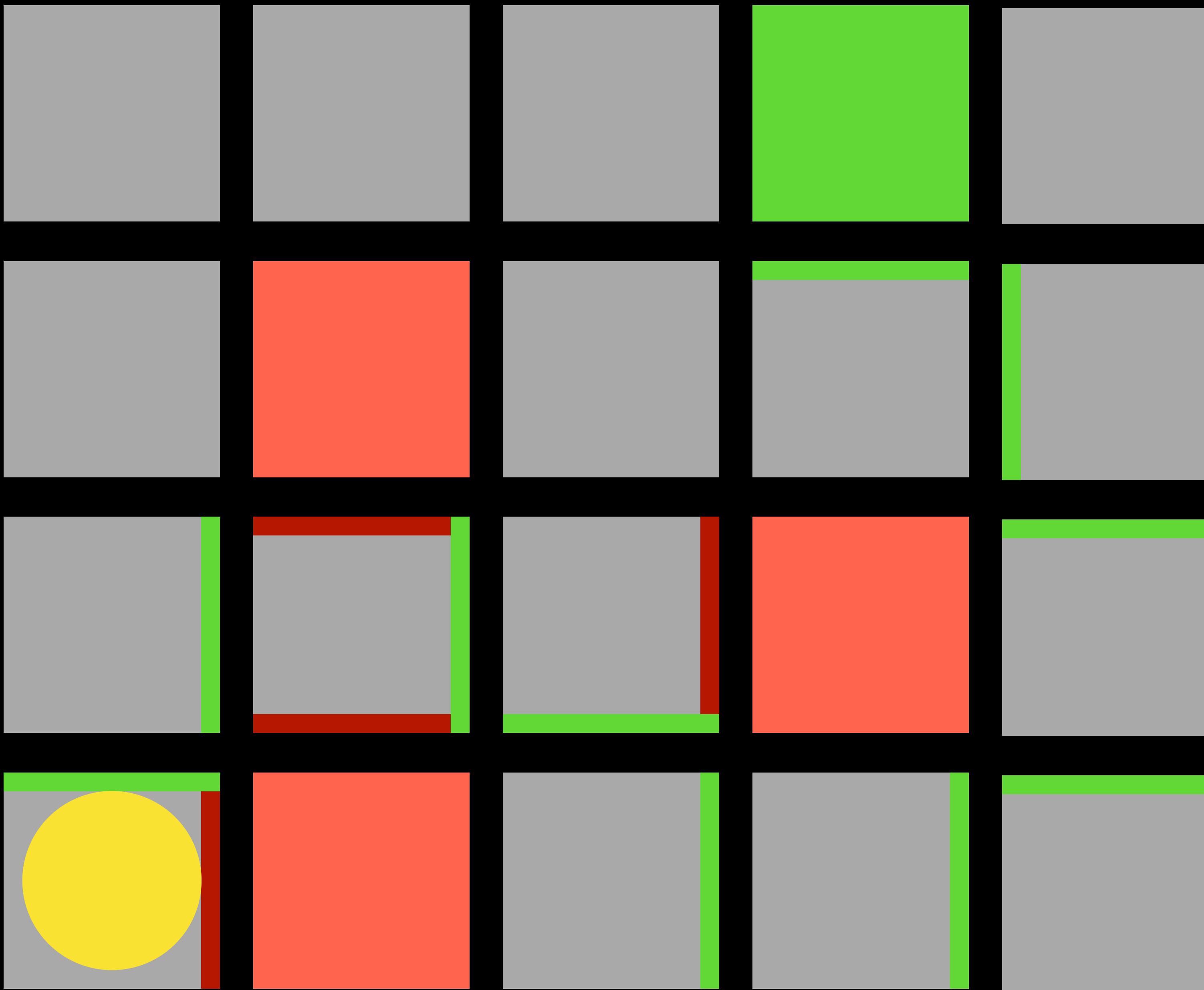












# Explore vs. Exploit

# Explore vs. Exploit Strategy

```
epsilon = 0.10
```

```
if random() < epsilon:  
    make a random move  
else:  
    make the move with the highest value
```

# **Robot Motor Skill Coordination with EM-based Reinforcement Learning**

**Petar Kormushev, Sylvain Calinon,  
and Darwin G. Caldwell**

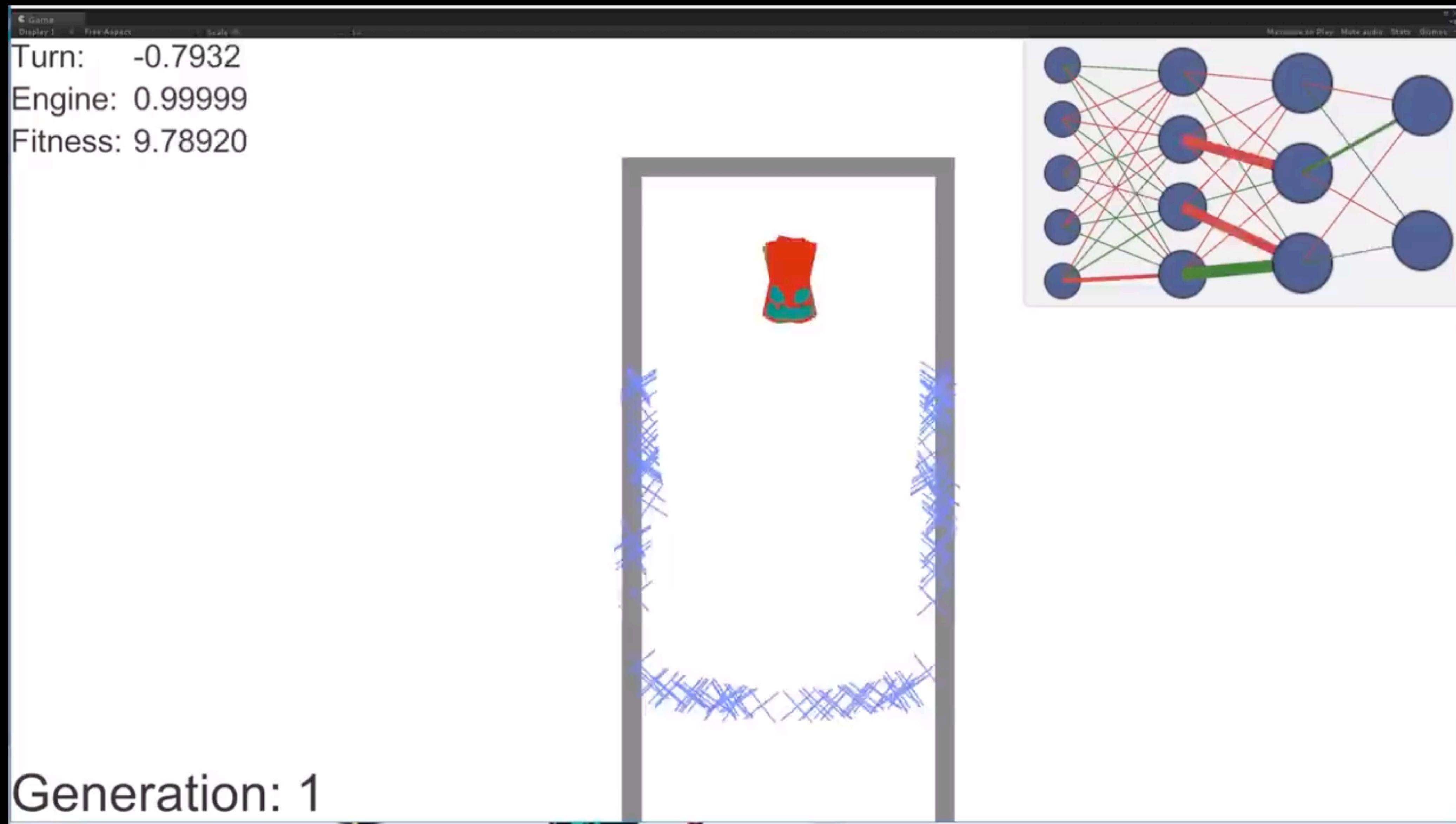
**Italian Institute of Technology**

[https://www.youtube.com/watch?v=W\\_gxLKSsSIE](https://www.youtube.com/watch?v=W_gxLKSsSIE)

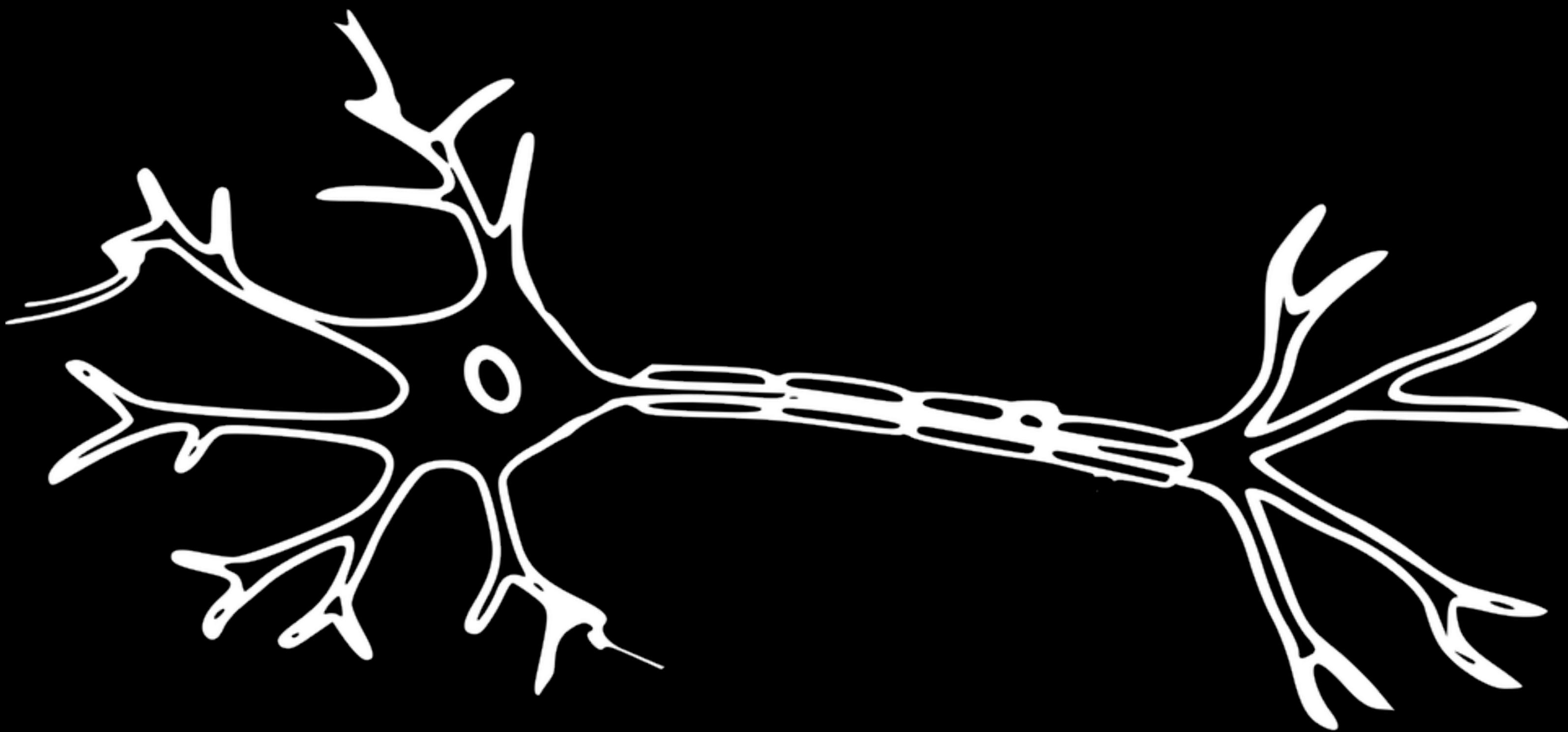
# Genetic Algorithms

# Genetic Algorithm

```
make initial generation of candidates randomly  
repeat until successful:  
    for each candidate:  
        calculate candidate's fitness  
    remove least fit candidates  
    make new generation from remaining candidates
```

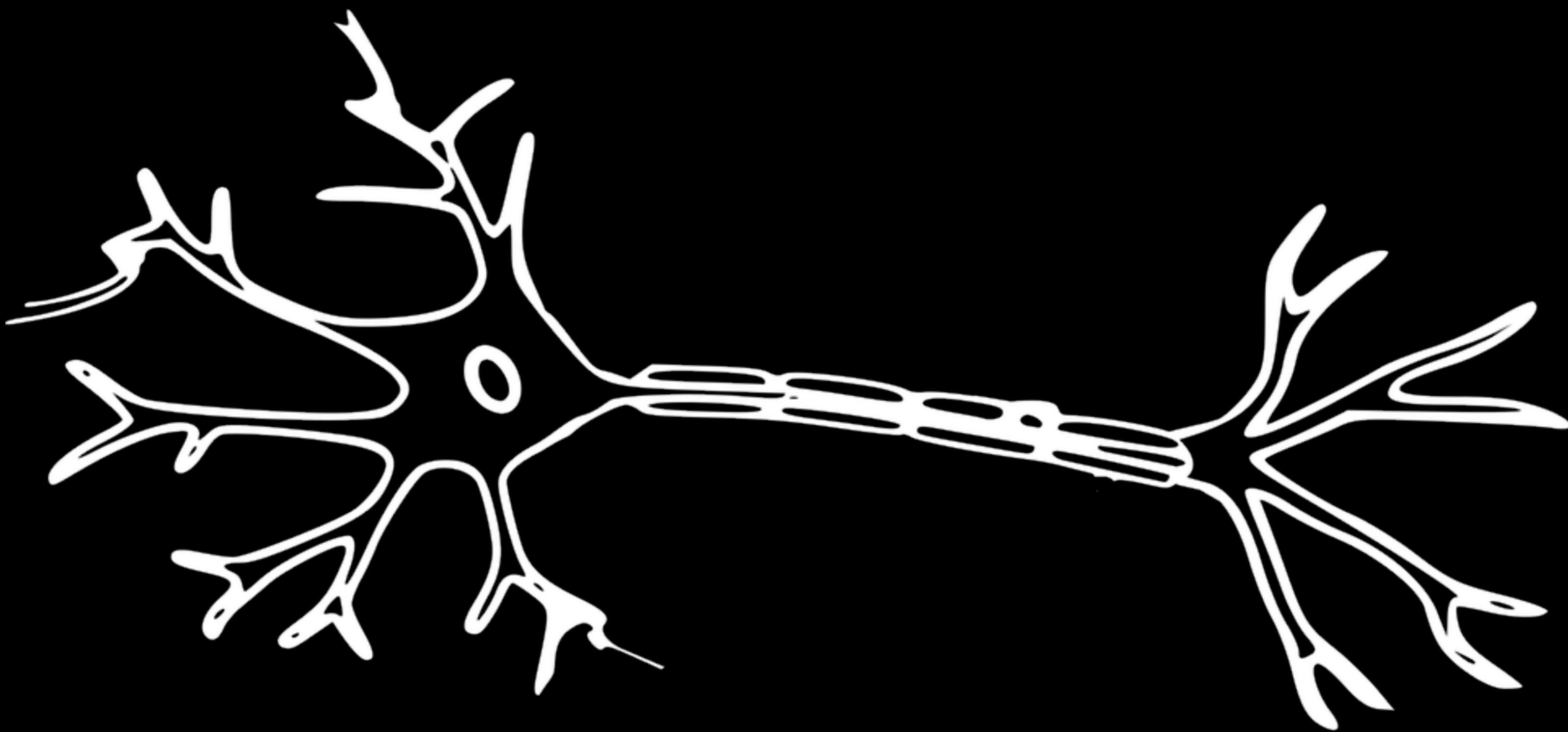


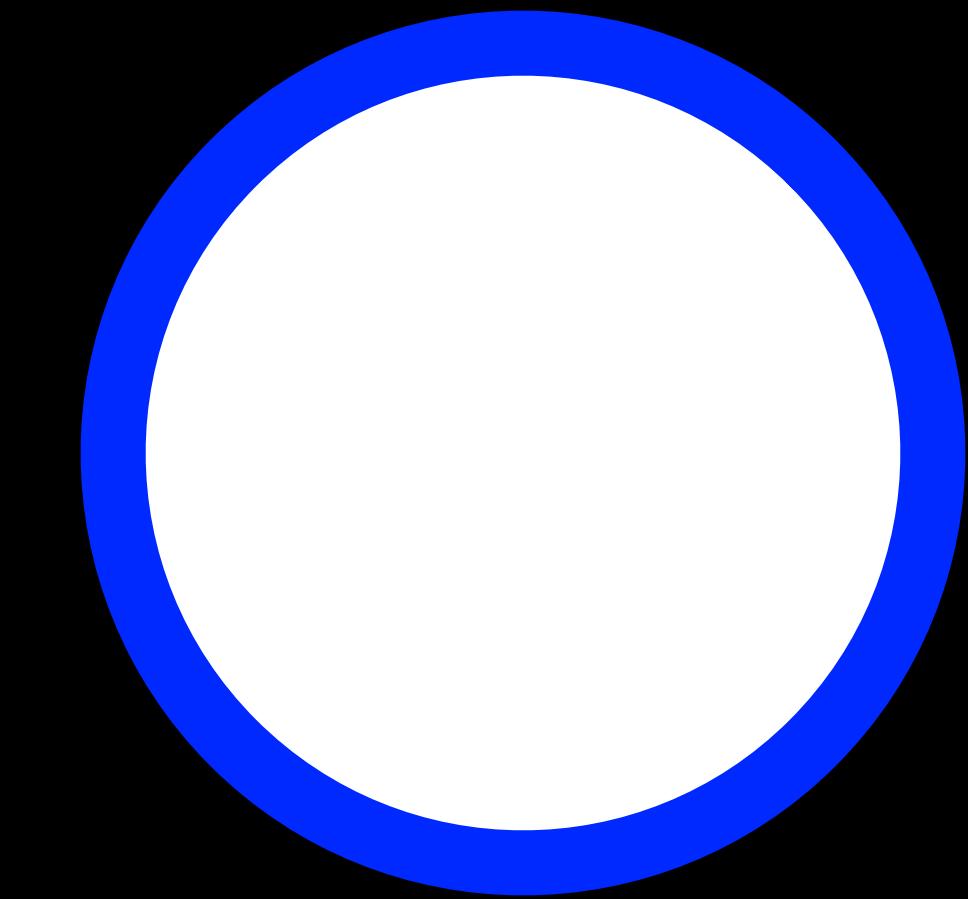


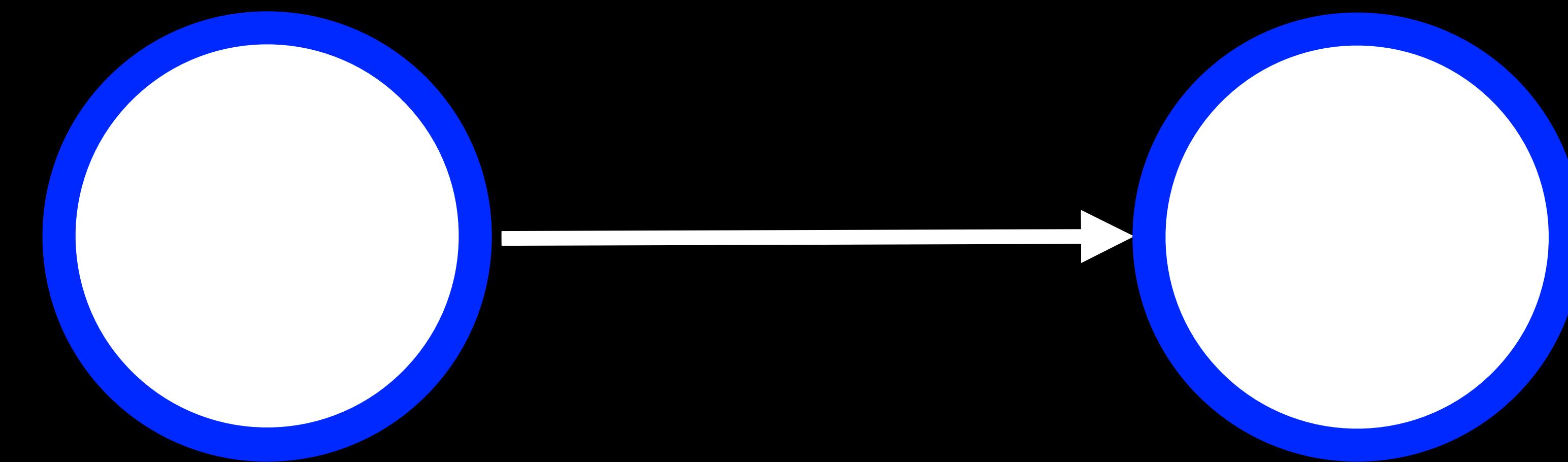


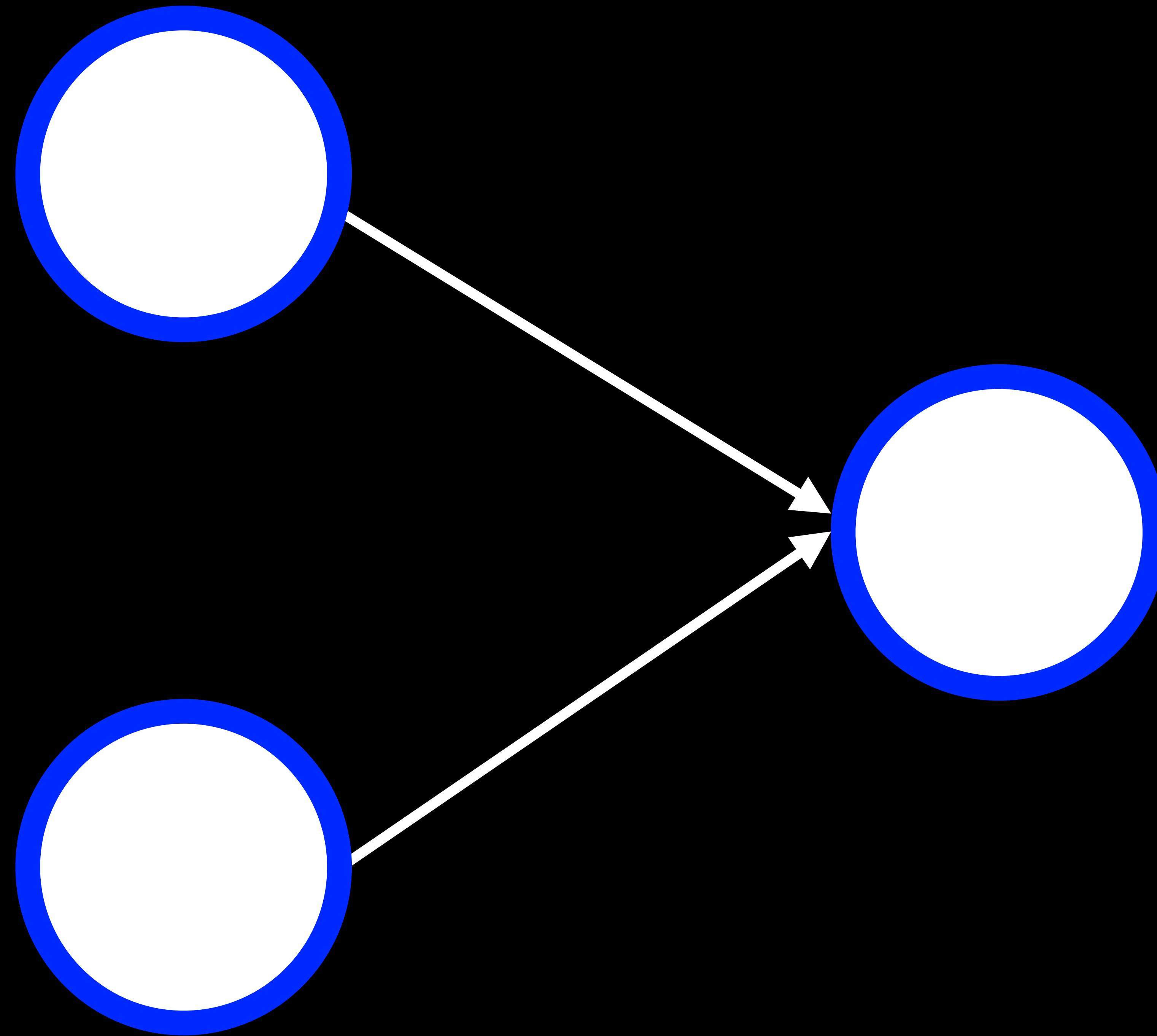


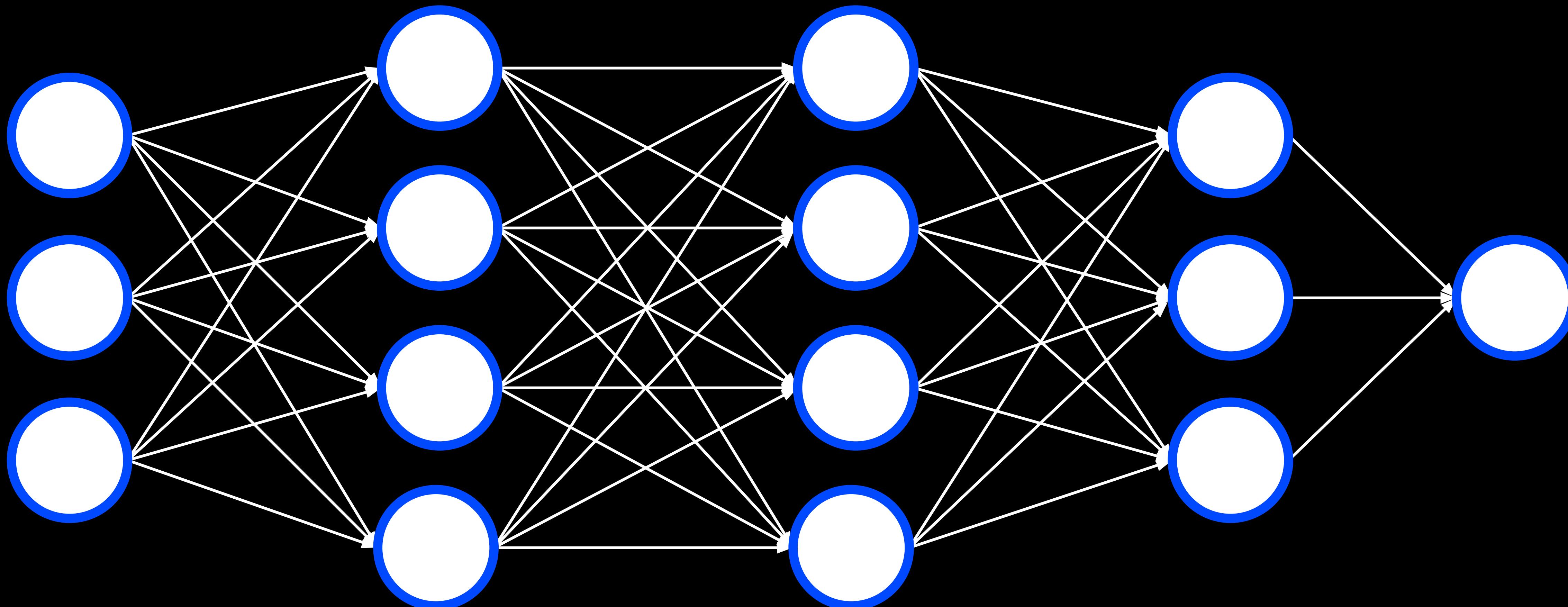
# Neural Networks

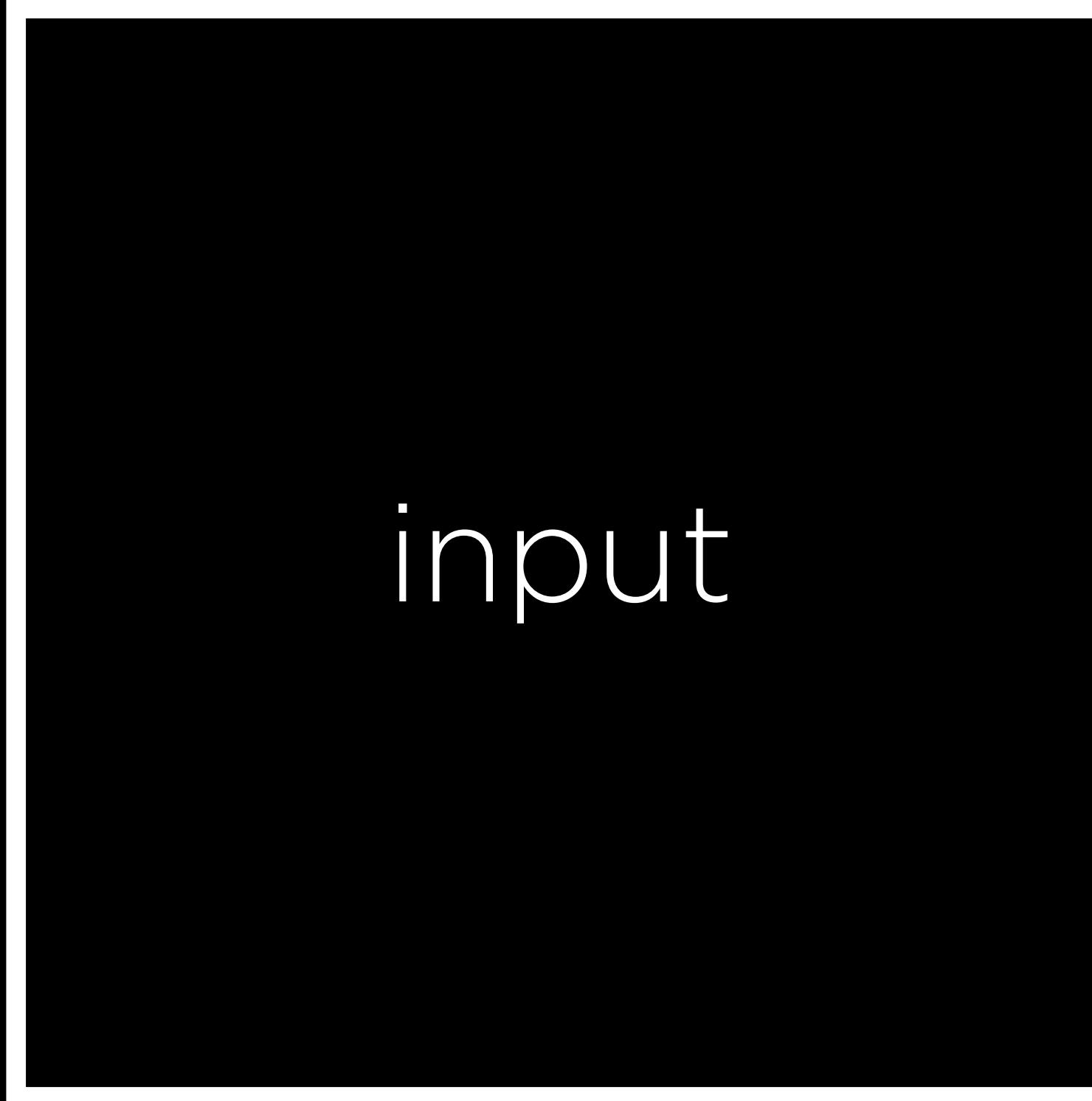




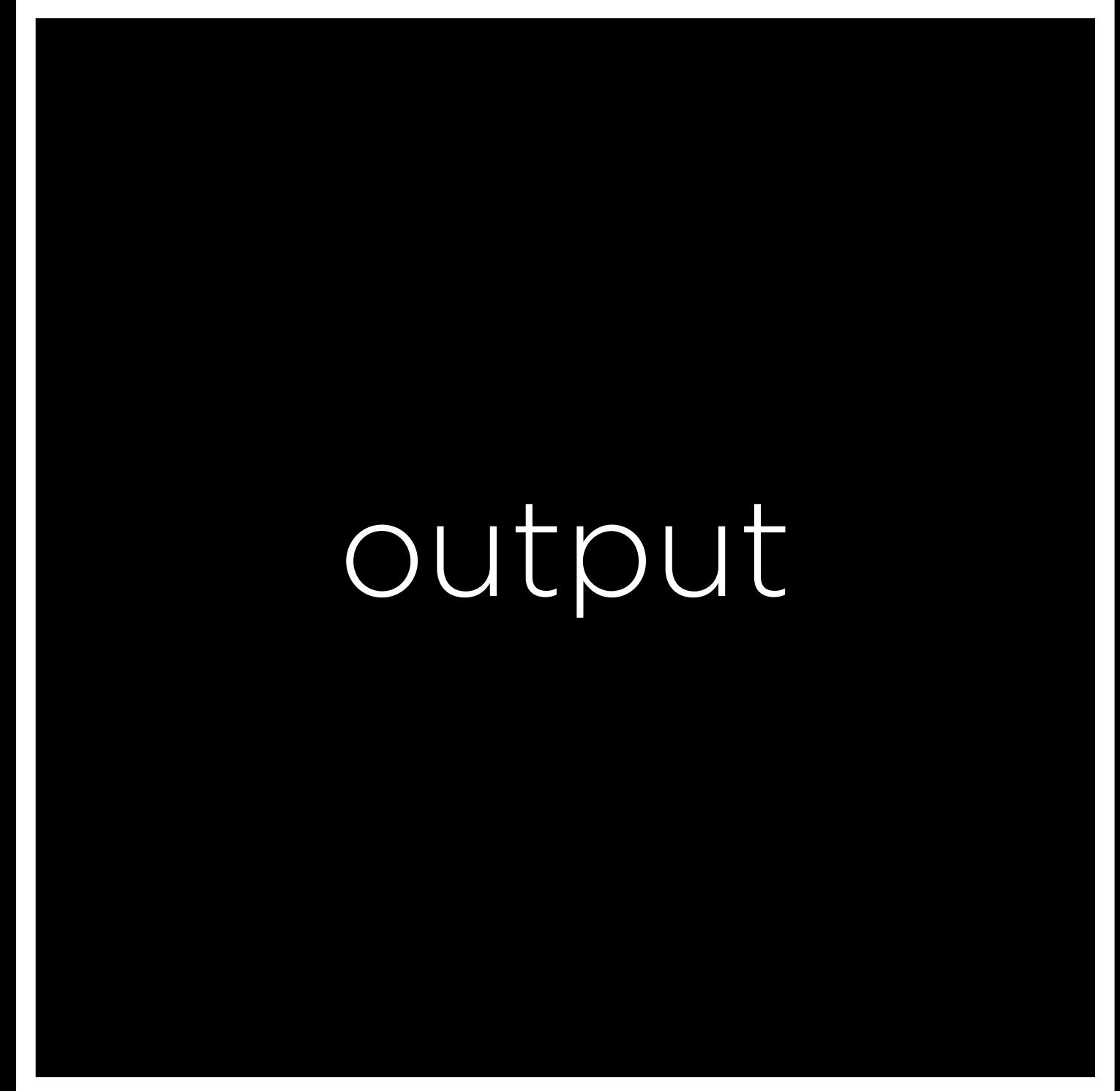






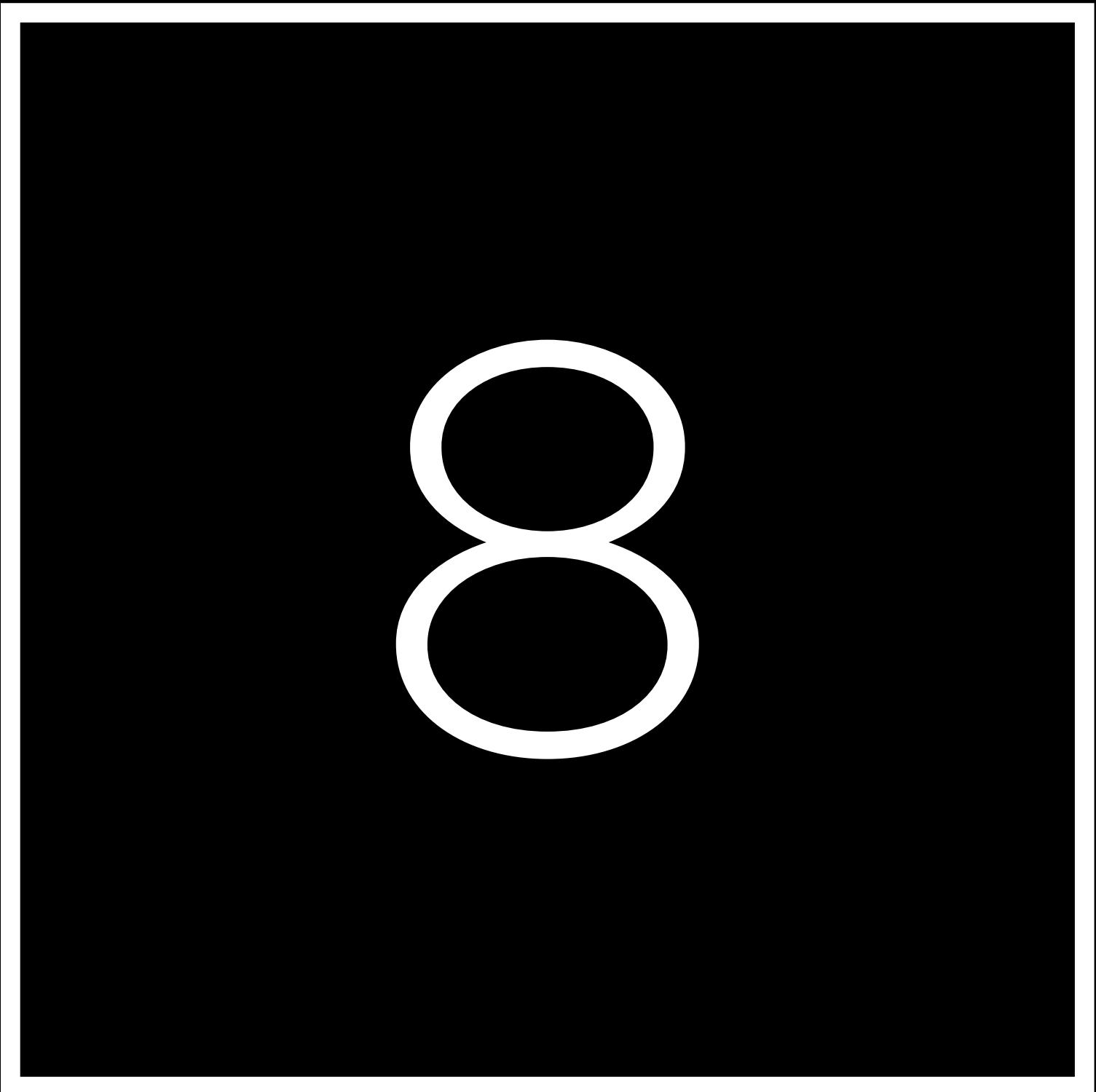


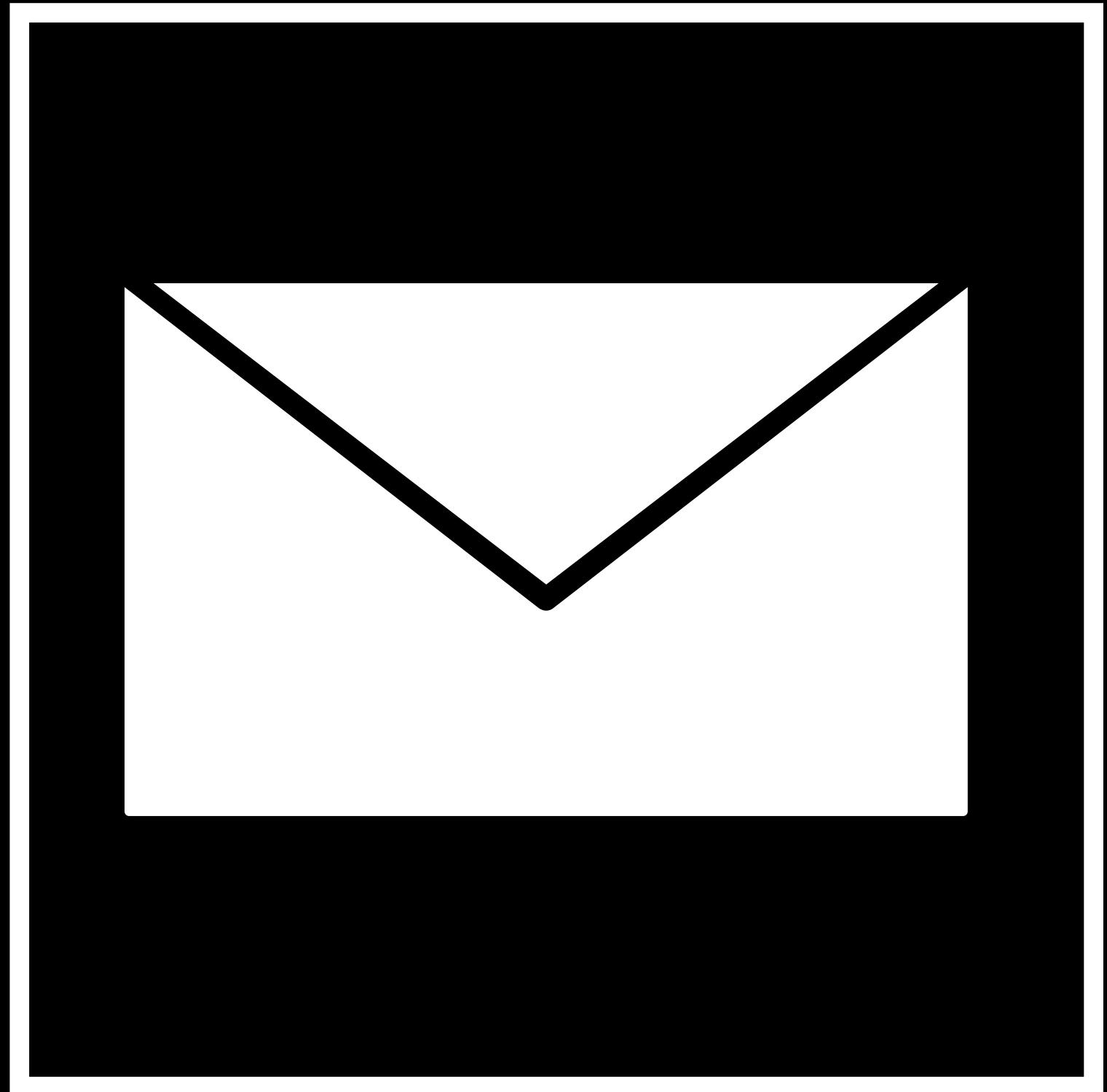
input



output







spam

A black square containing the word "spam" written in a white, sans-serif font.









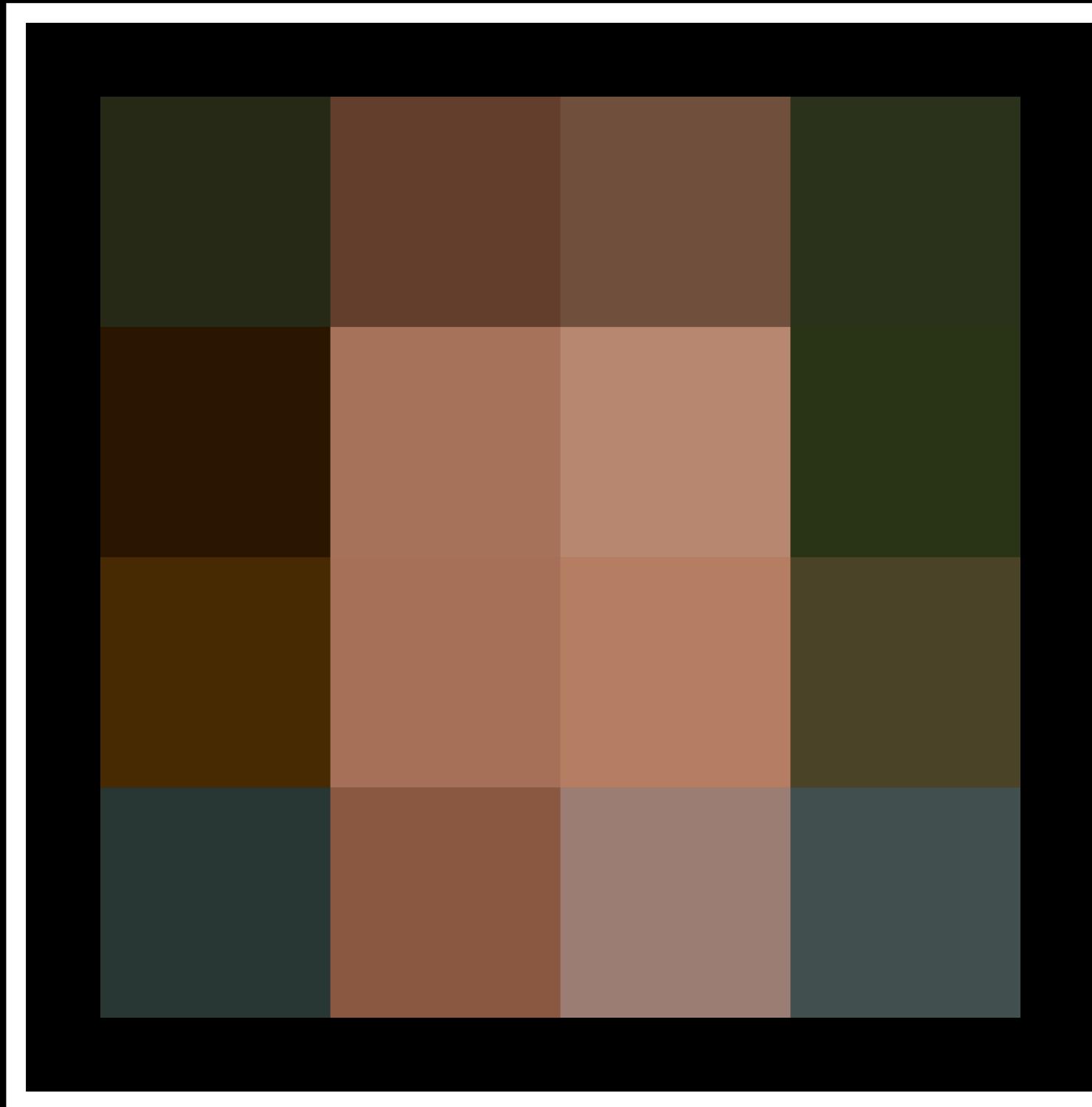












# Artificial Intelligence