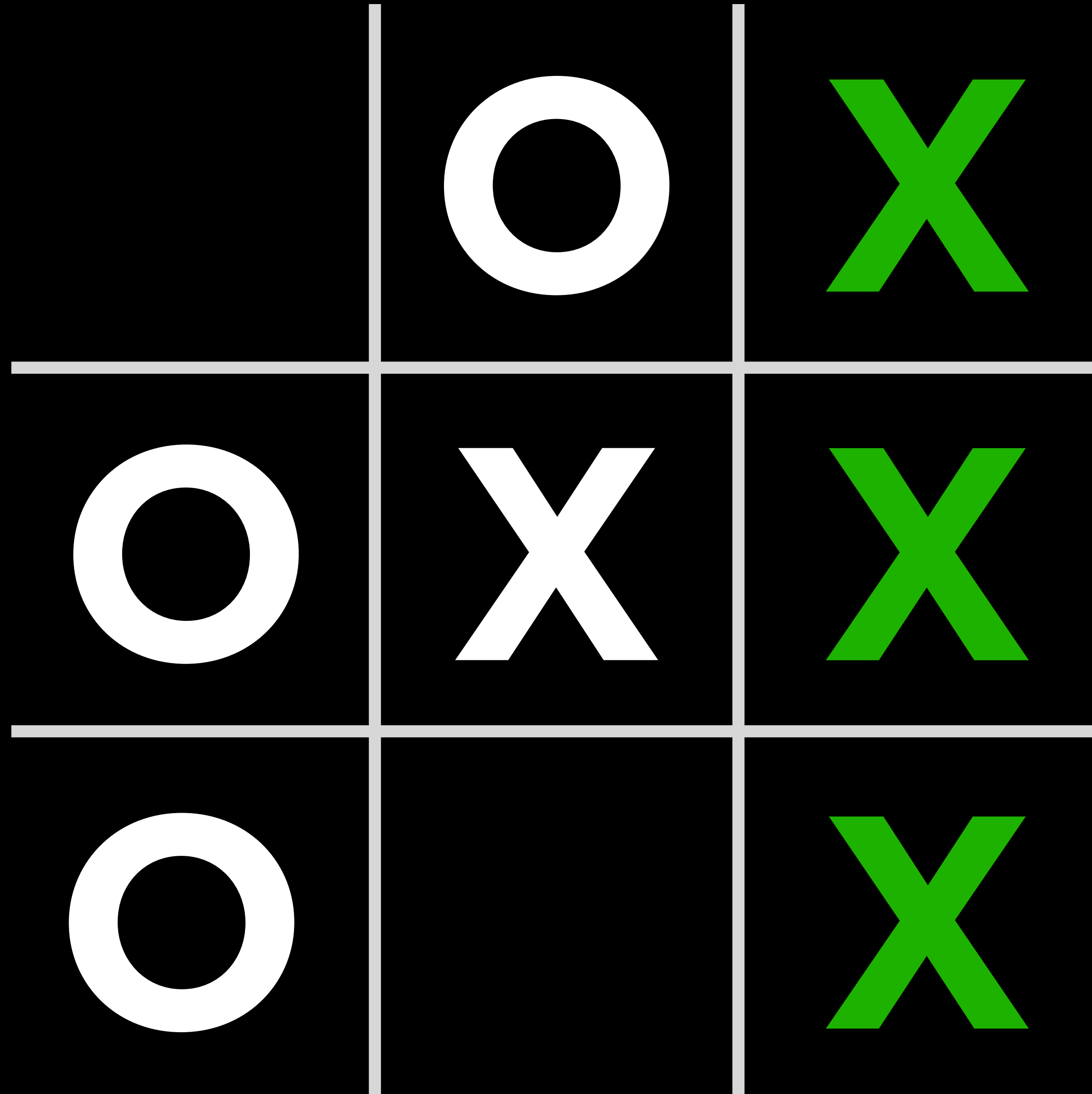
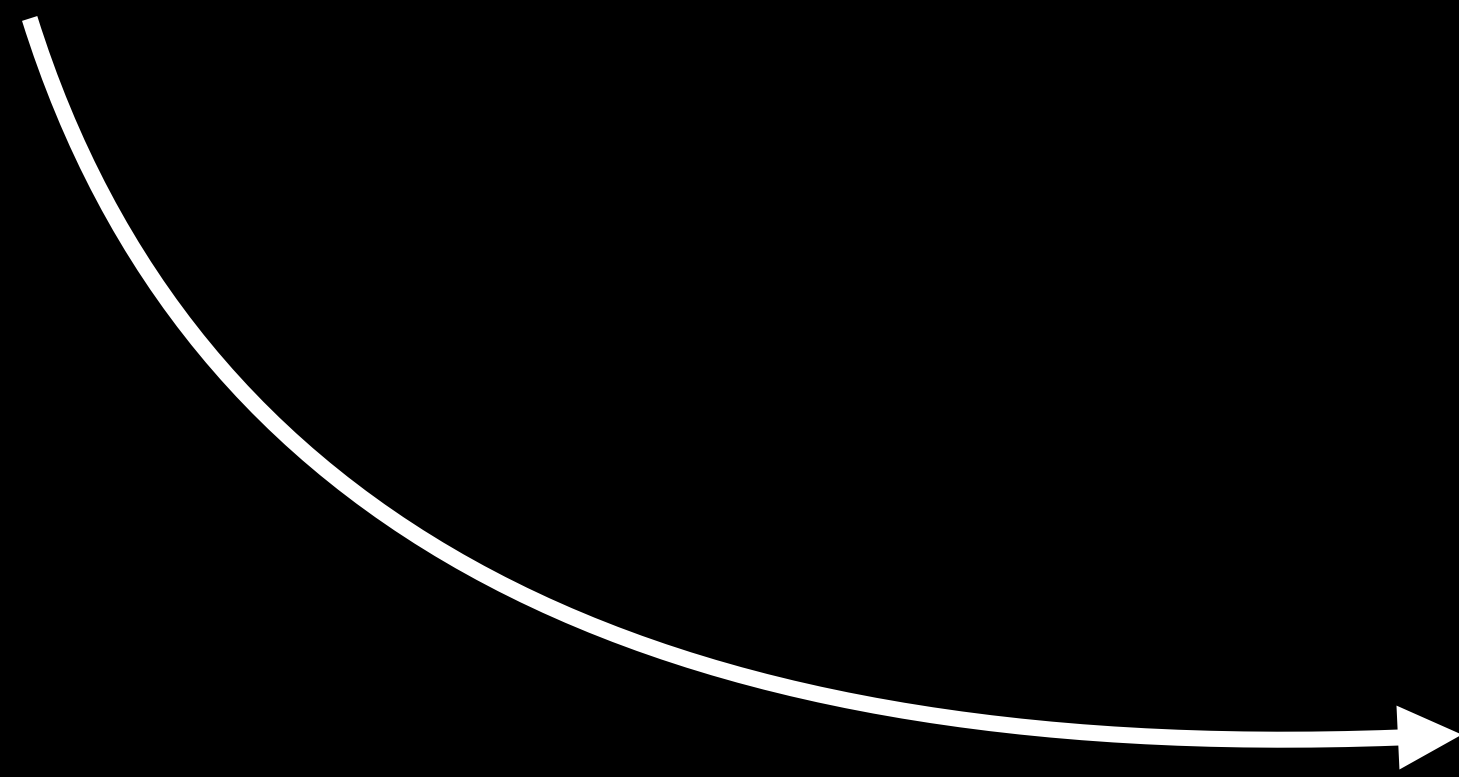


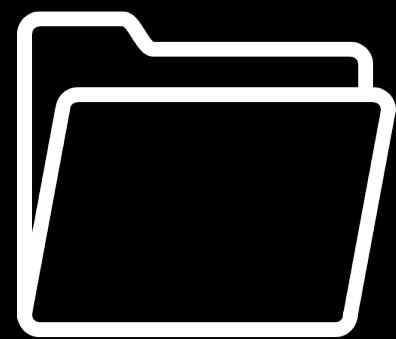
# Artificial Intelligence



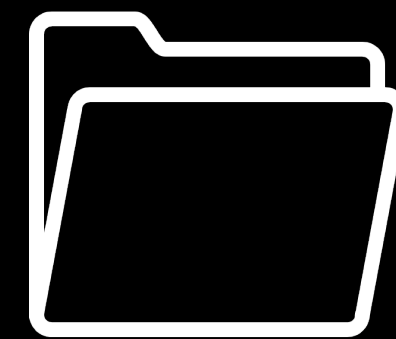
handwriting



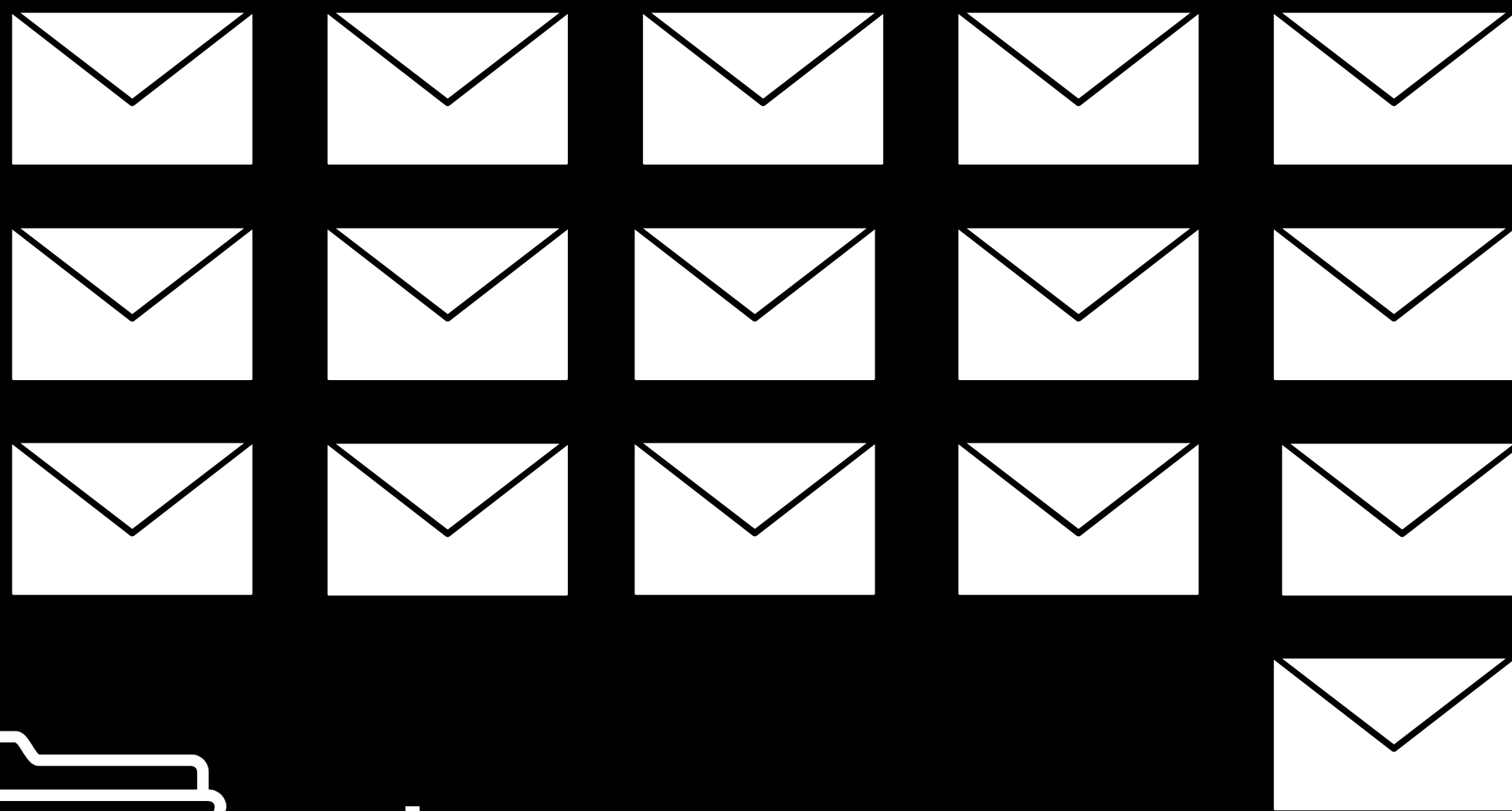
handwriting



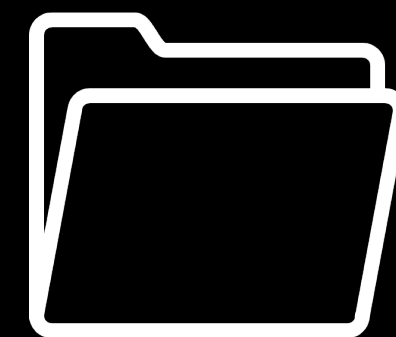
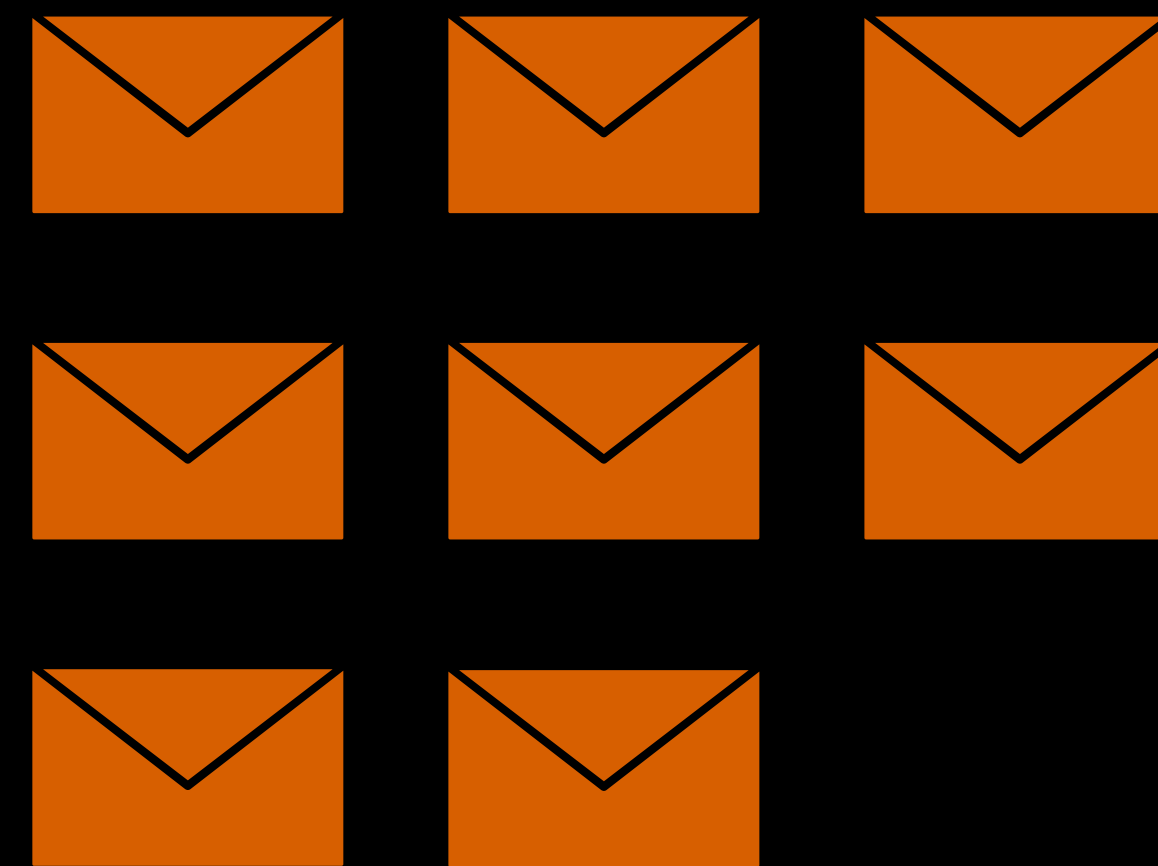
**Inbox**



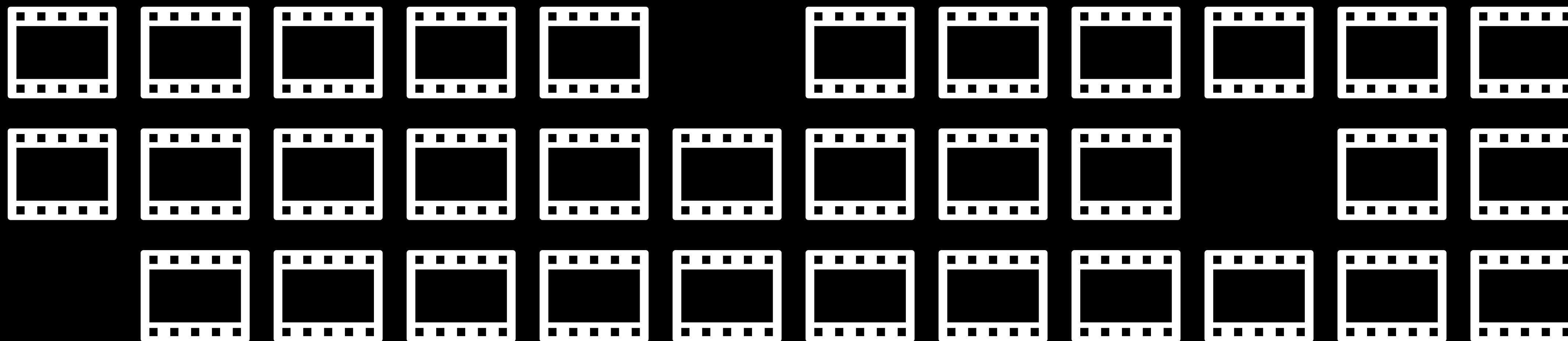
**Spam**



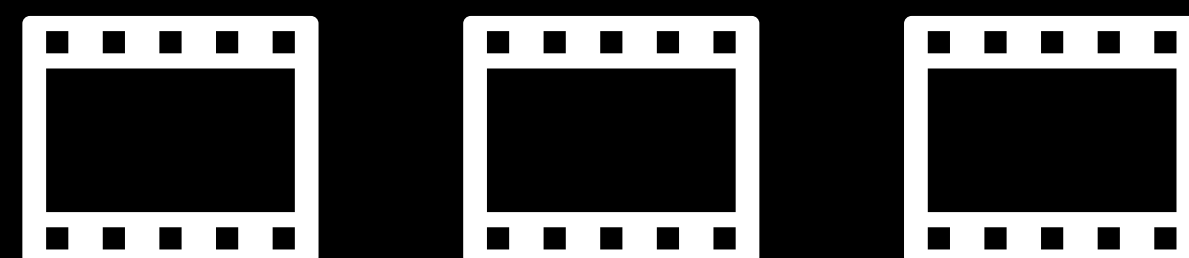
**Inbox**



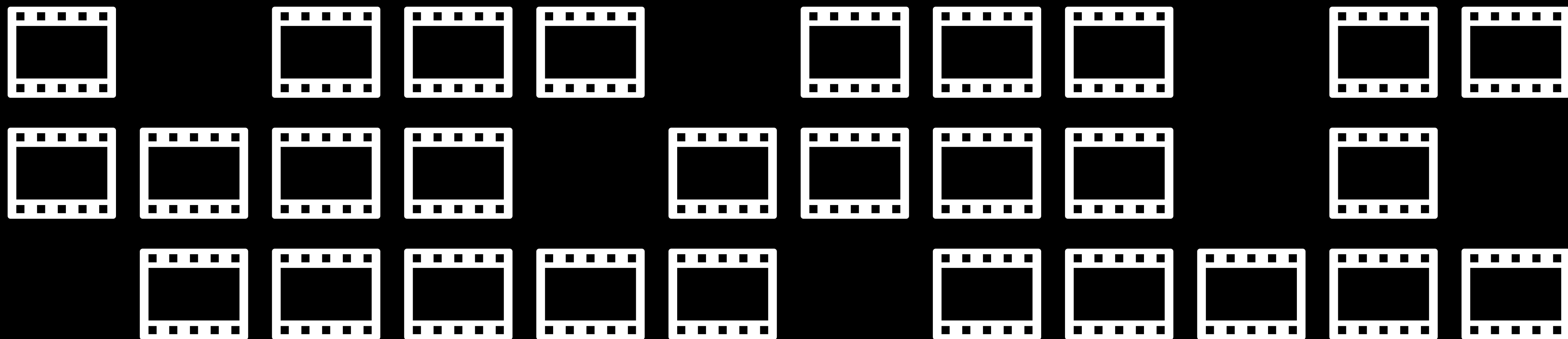
**Spam**



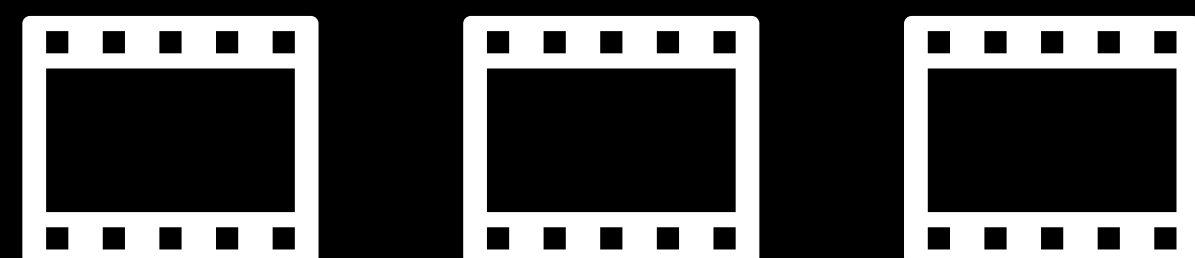
Watch History



Recommended



Watch History



Recommended

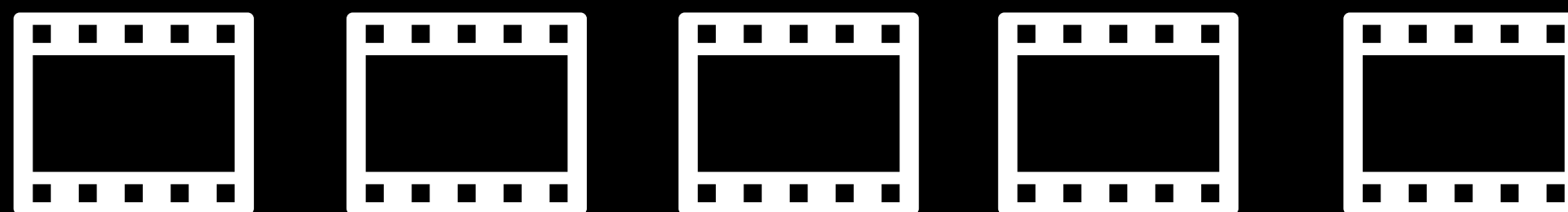


Image 1



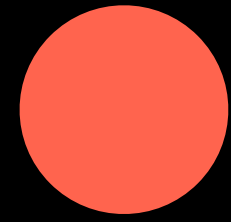
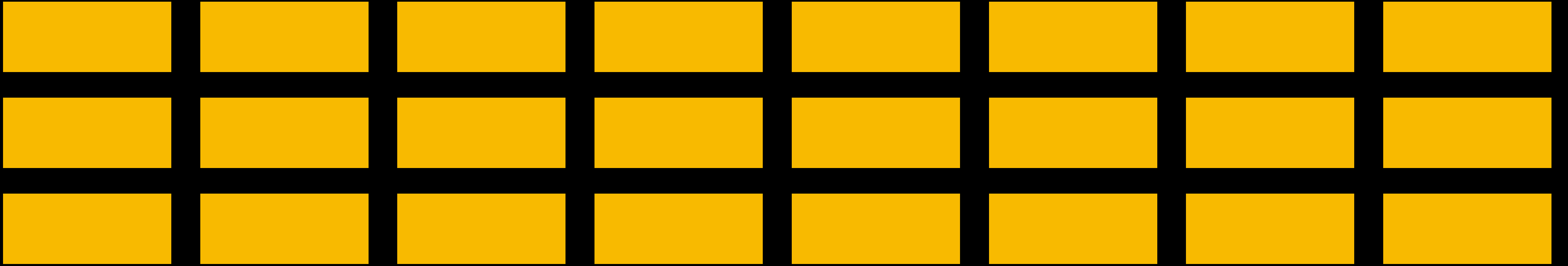
Image 2





# Artificial Intelligence

# Decision-Making



# Decision Trees

Is ball left of paddle?

Yes

No

Move paddle left.

Is ball right of paddle?

Yes

No

Move paddle right.

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
```

		O
	X	
X		O

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.

O	X	X
O	O	
O	X	X

-1

X	O	X
O	O	X
X	X	O

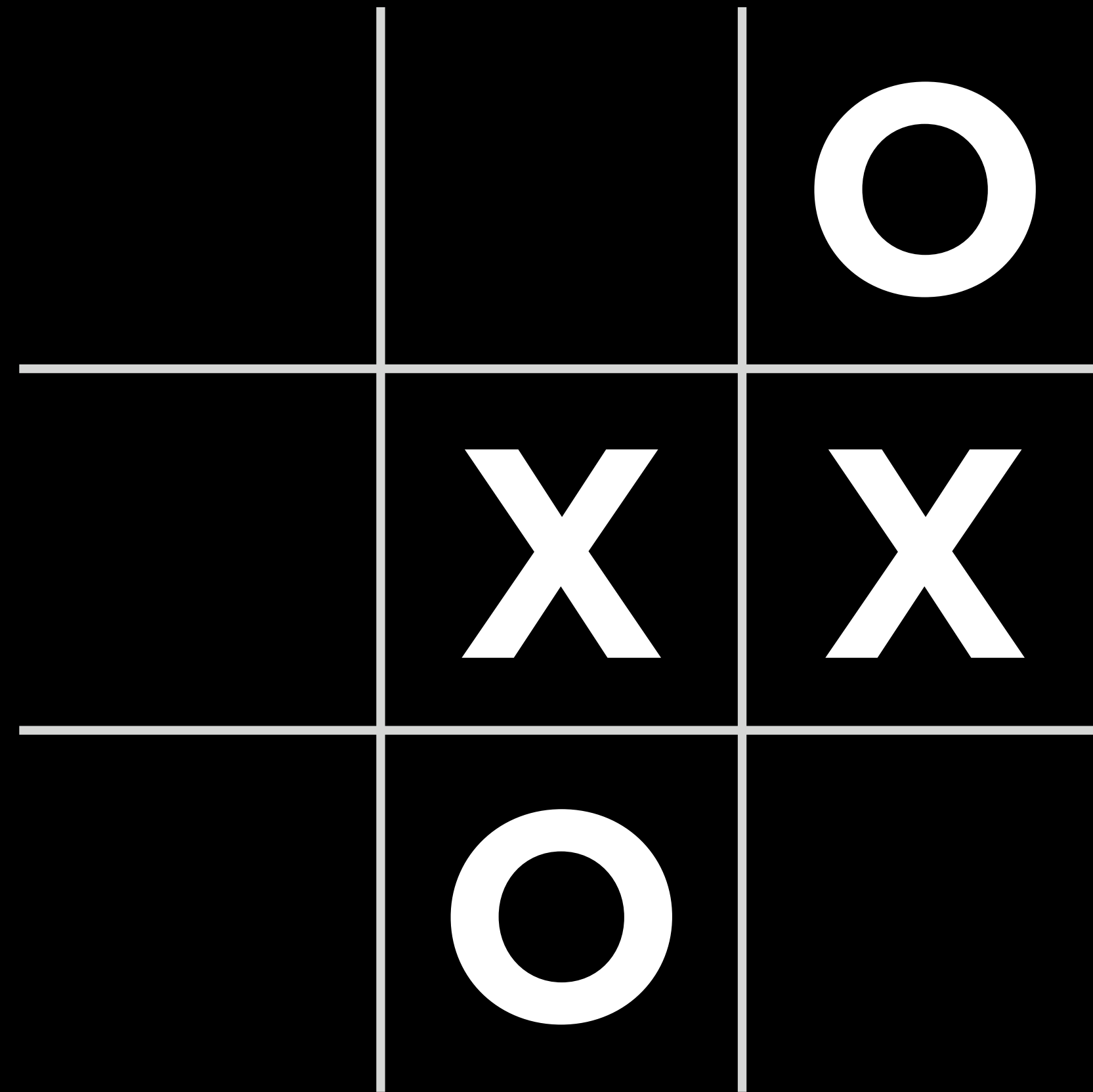
0

O		X
	X	O
X	O	X

1

O	X	O
O	X	X
X	X	O

VALUE: 1



**X's Turn**

VALUE: 1

	X	O
O	X	X
X		O

O's Turn

VALUE: ?

Turn: O

VALUE:  
 $\emptyset$

	X	O
O	X	X
X		O

VALUE:  
1

O	X	O
O	X	X
X		O

VALUE:  
 $\emptyset$

	X	O
O	X	X
X	O	O

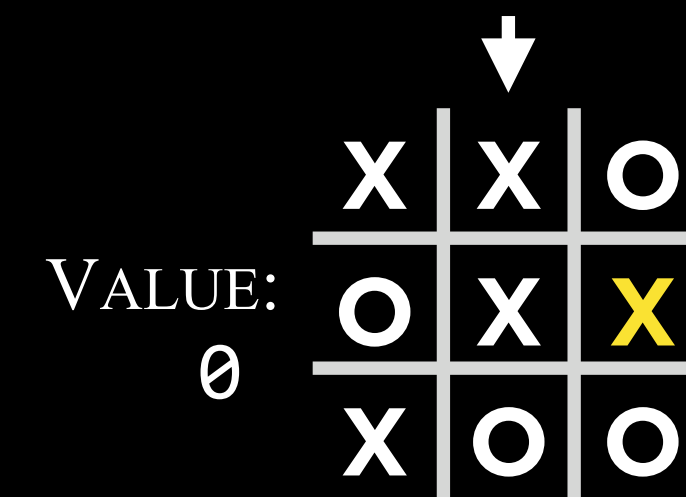
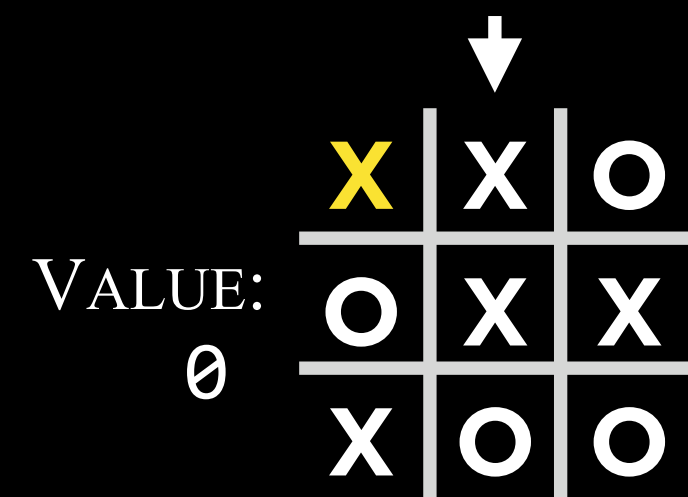
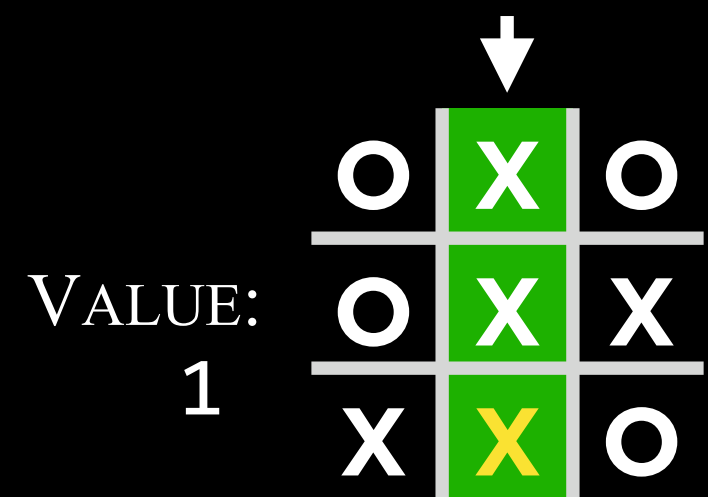
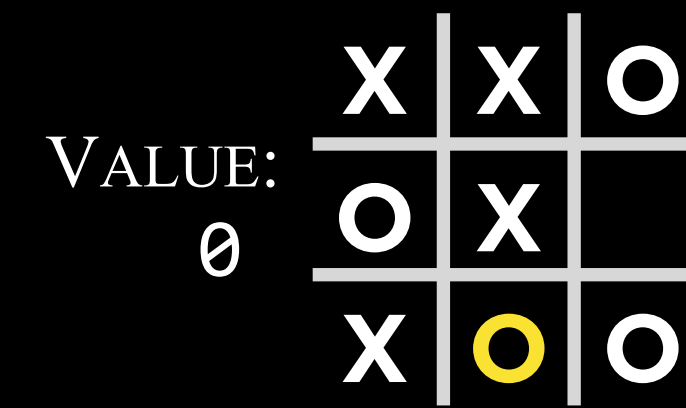
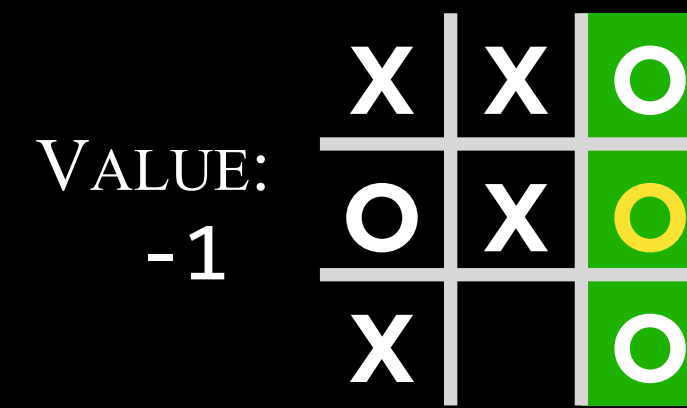
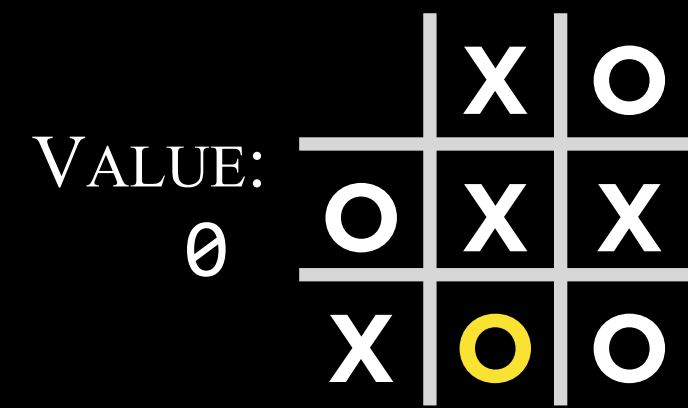
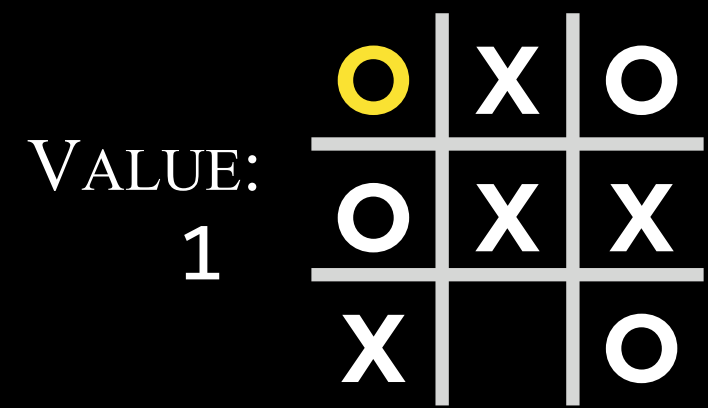
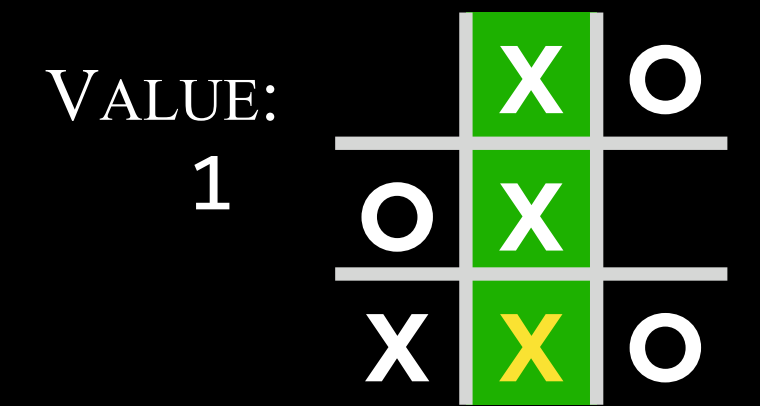
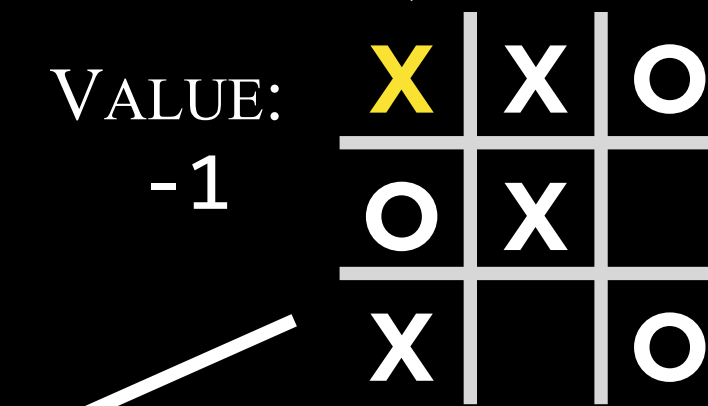
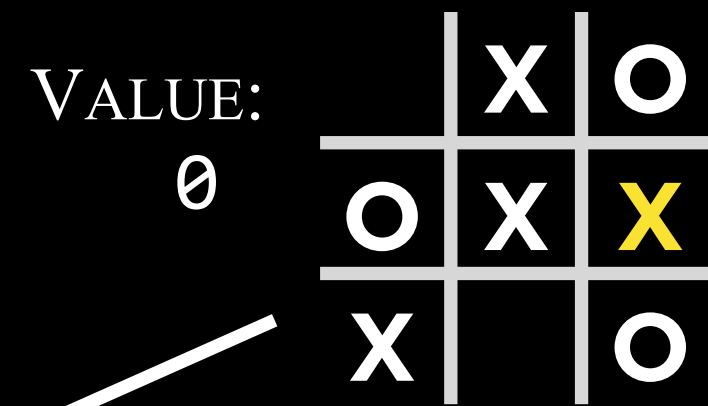
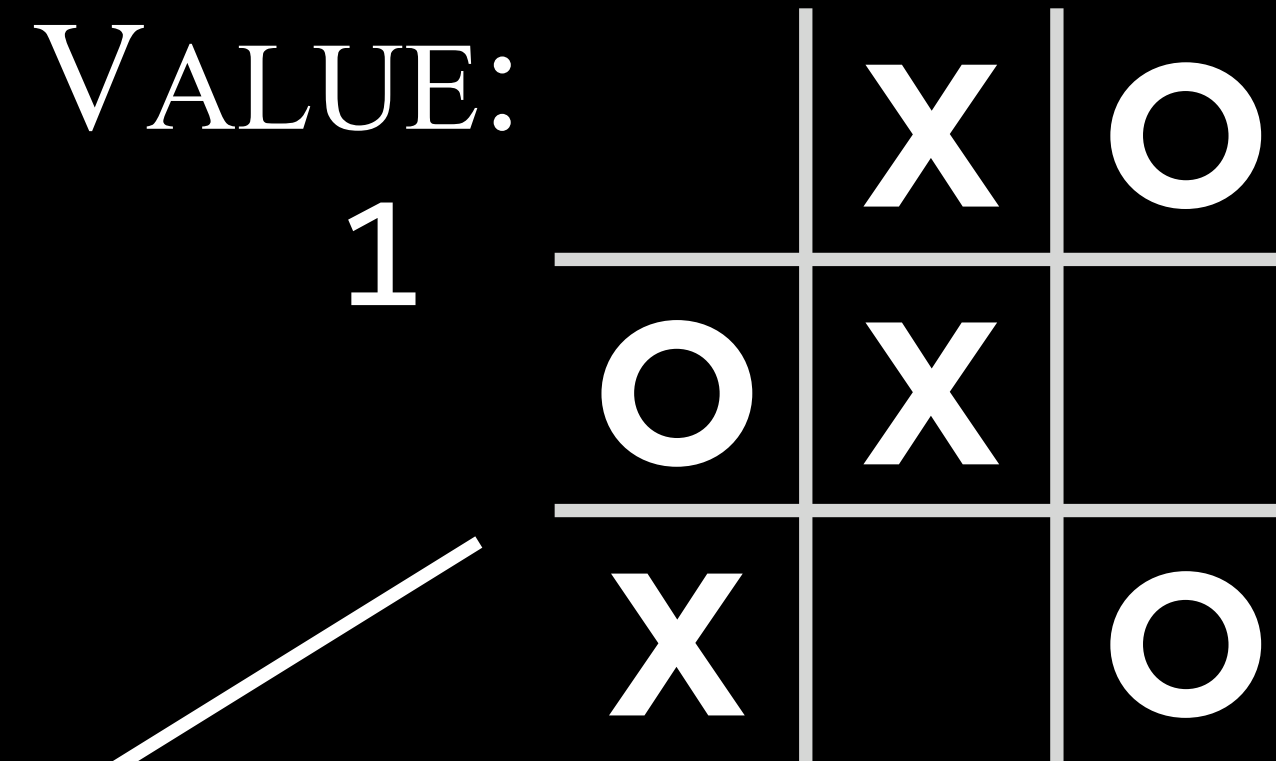
VALUE:  
1

O	X	O
O	X	X
X	X	O

VALUE:  
 $\emptyset$

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)

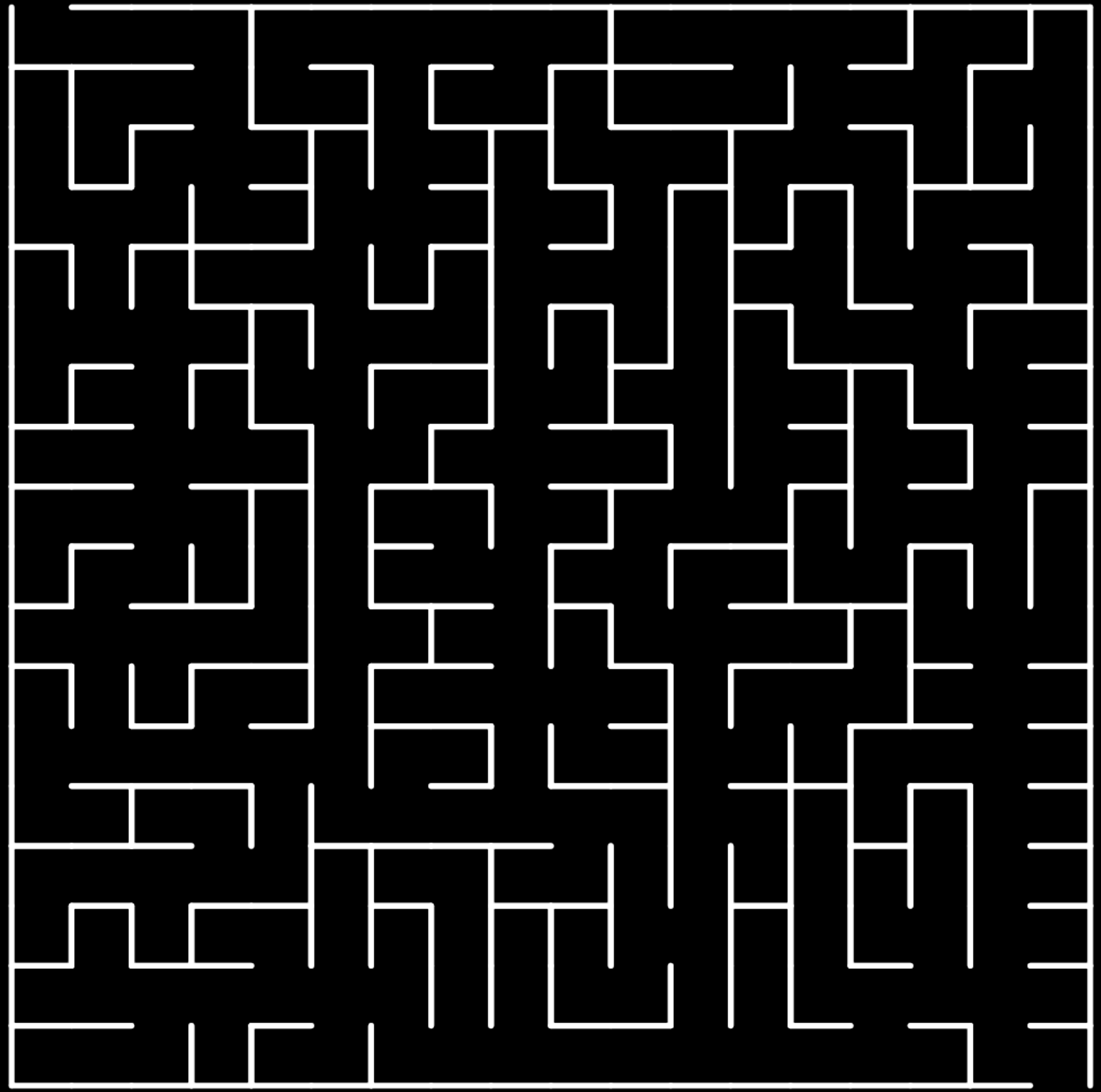
# Depth-Limited Minimax

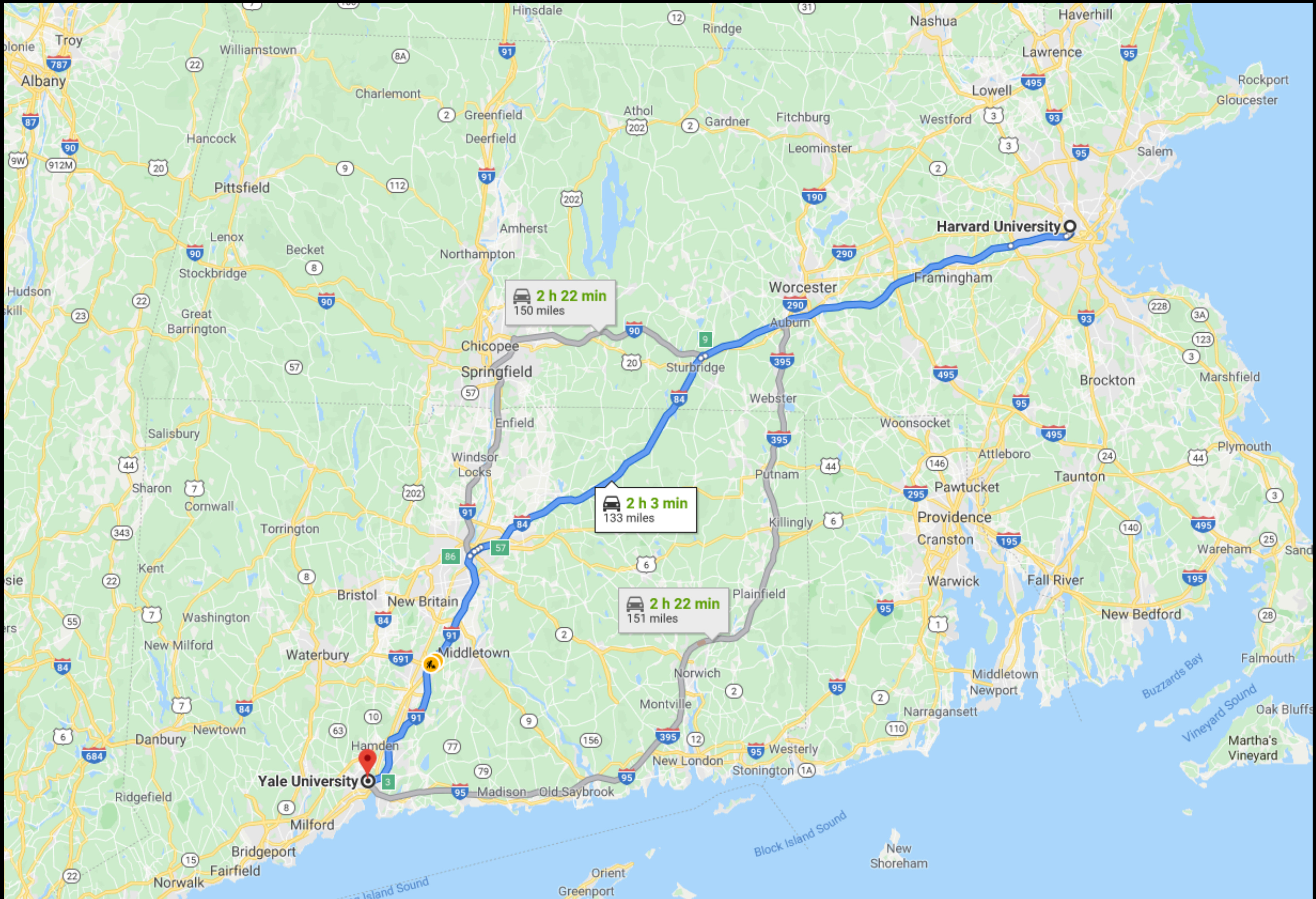
# evaluation function

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

**Search**





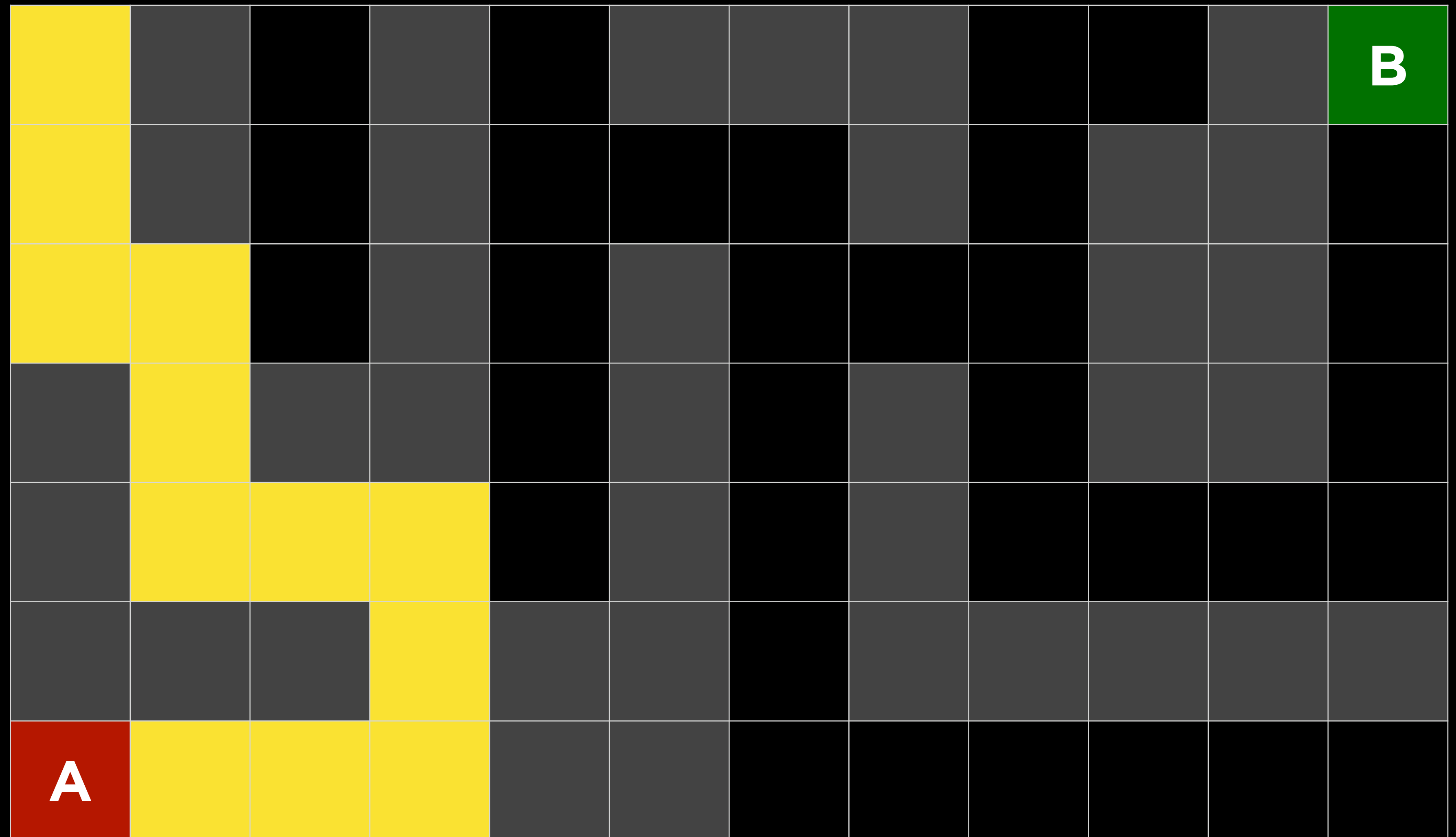




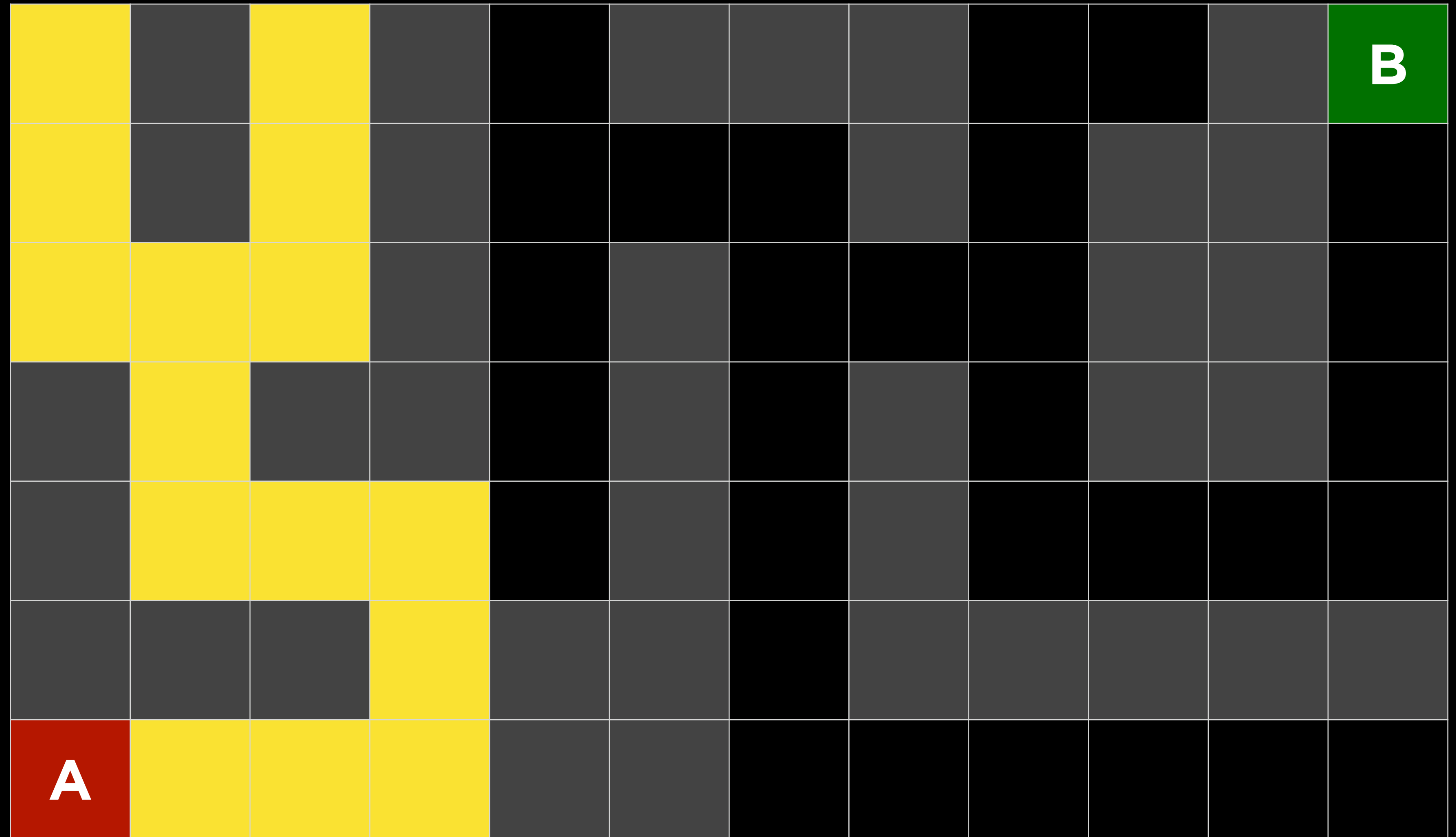
# Depth-First Search



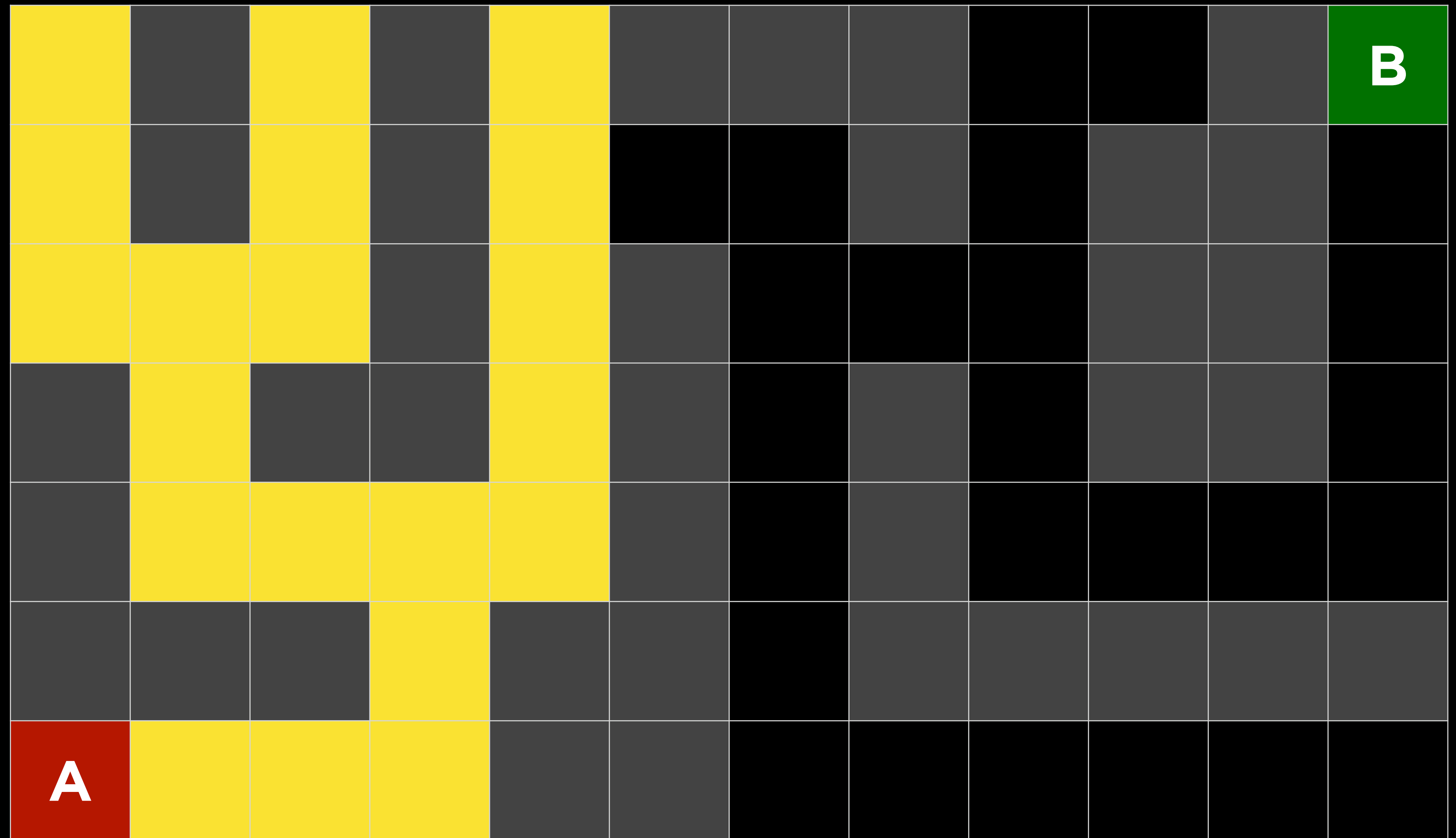
# Depth-First Search



# Depth-First Search

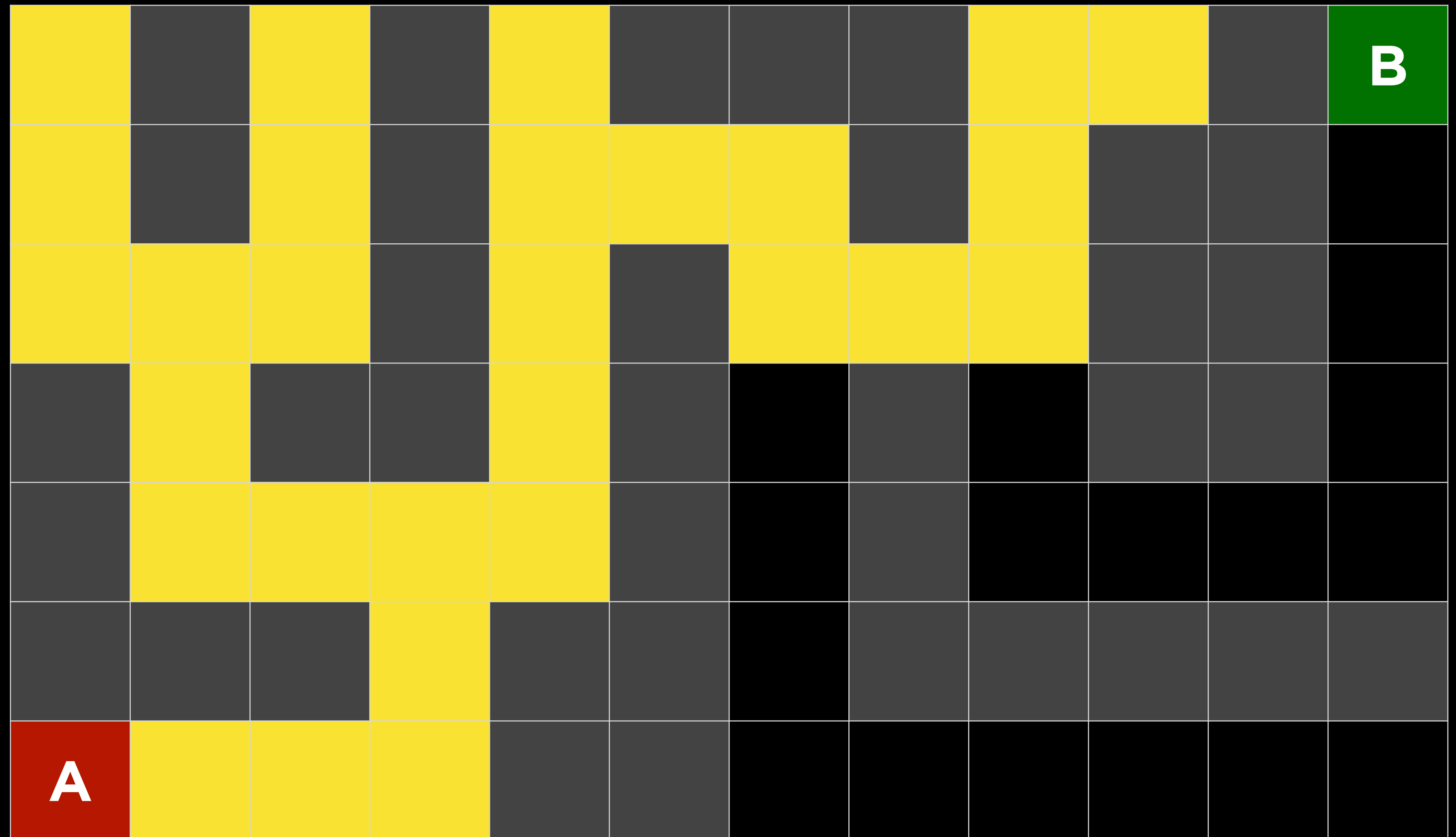


# Depth-First Search



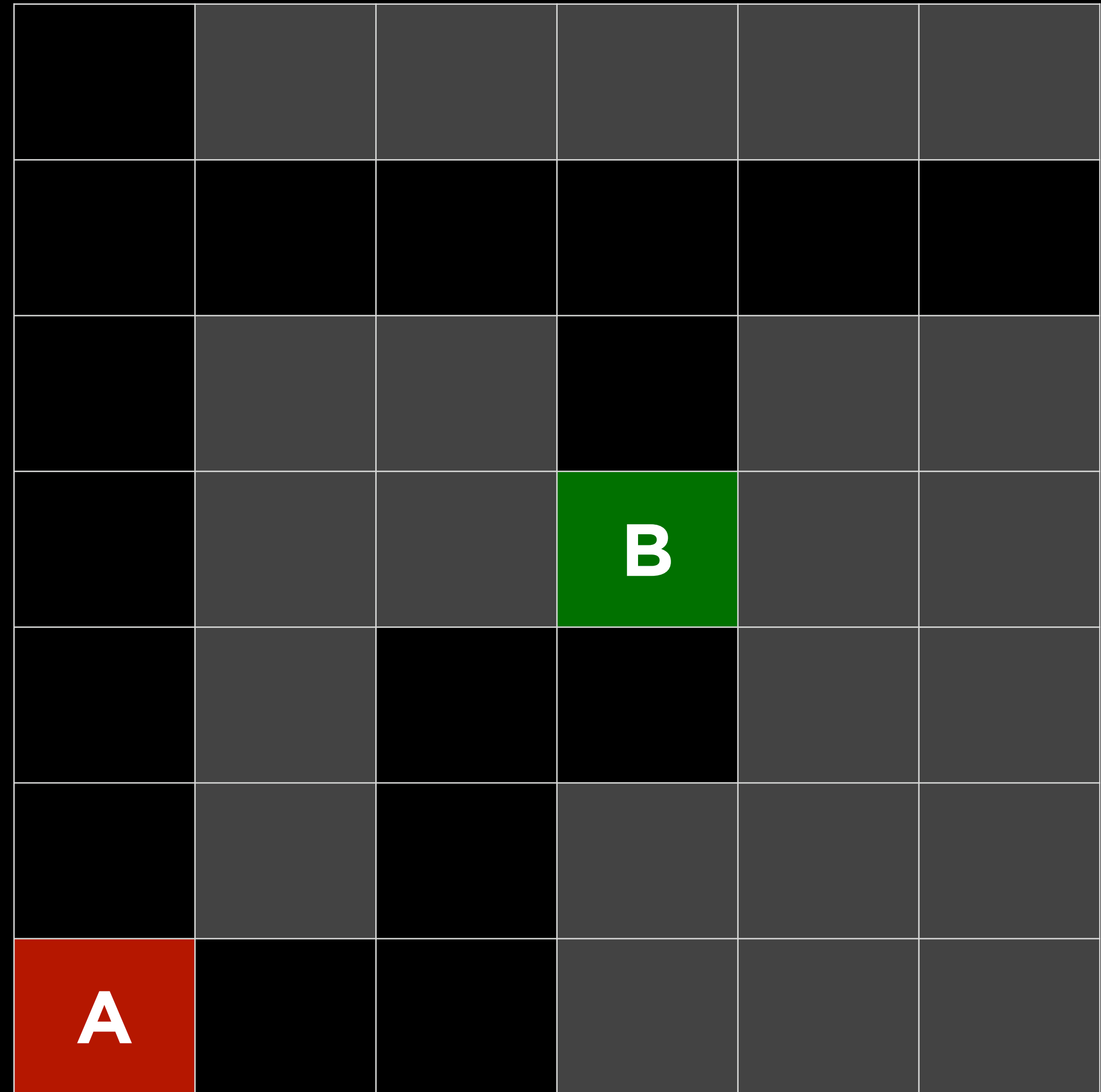


# Depth-First Search

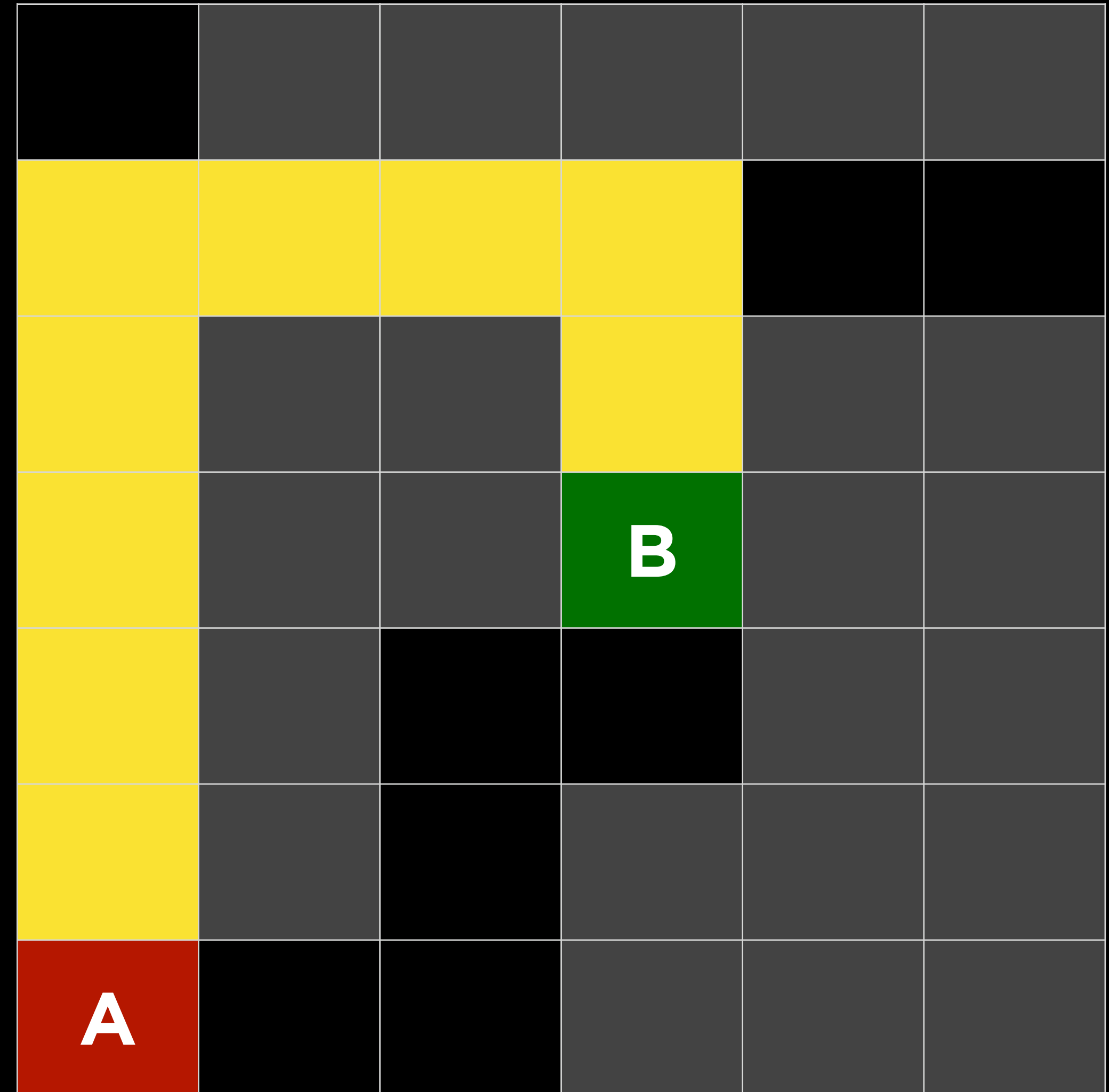




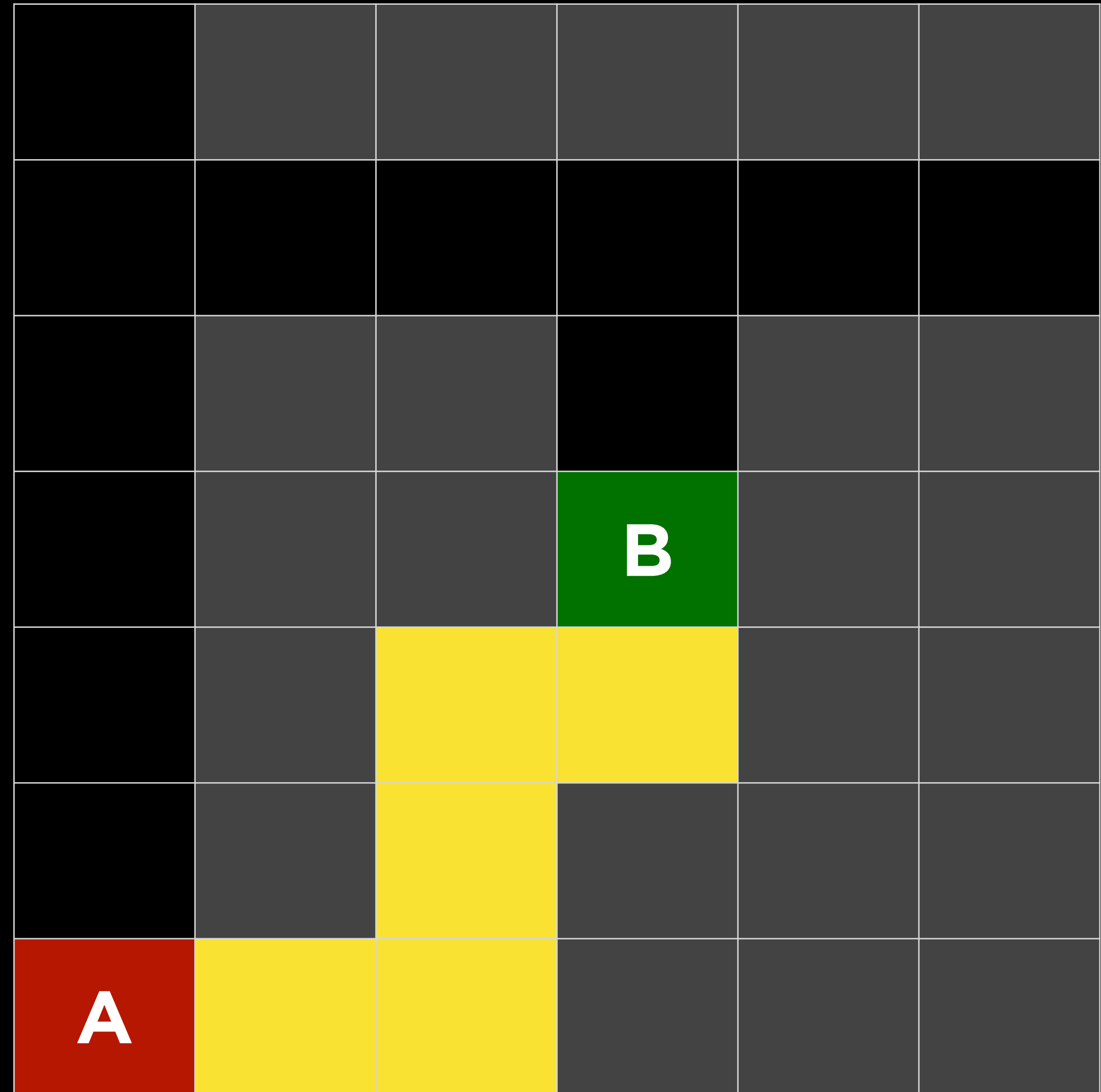
# Depth-First Search



# Depth-First Search

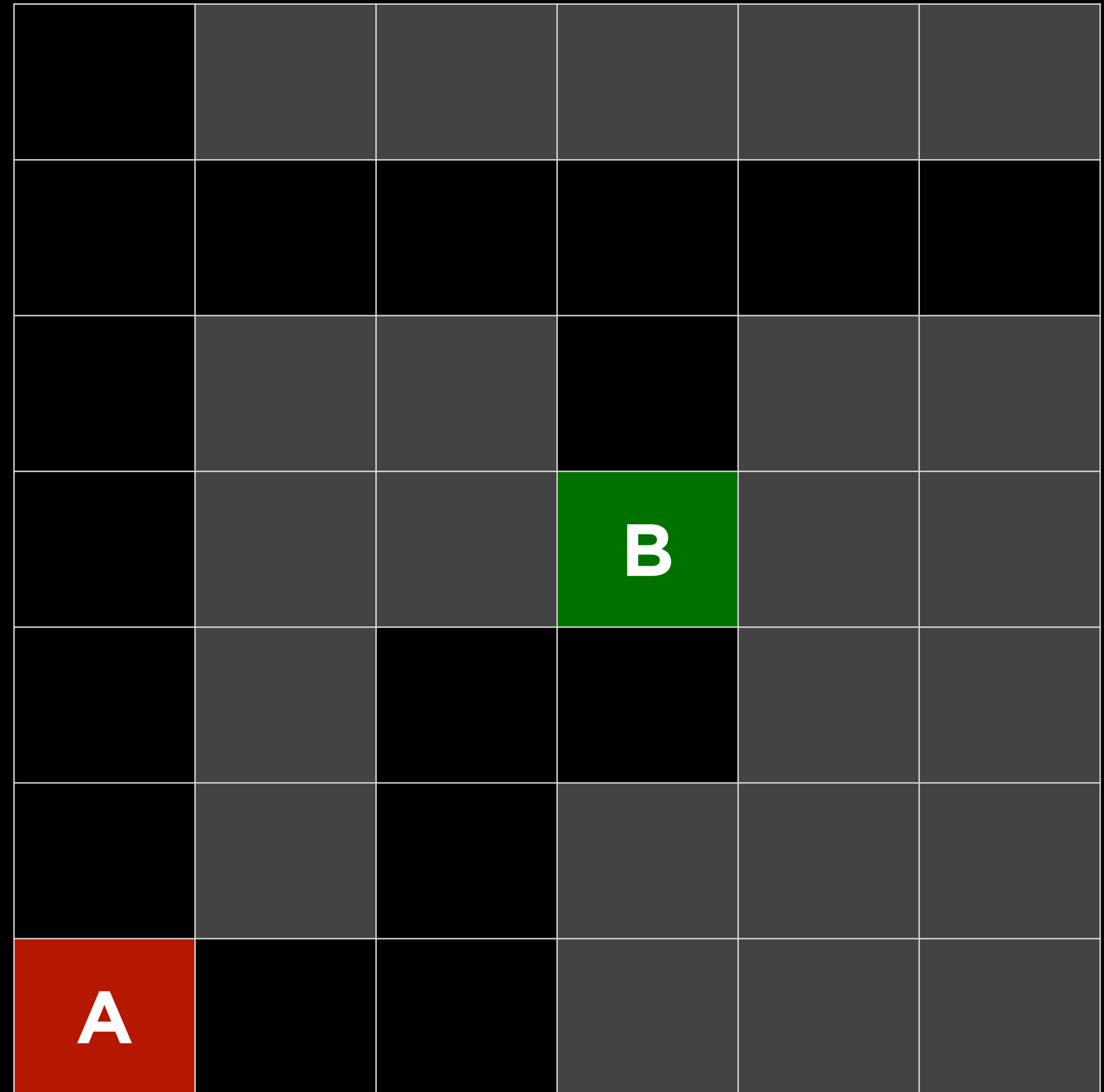


# Depth-First Search

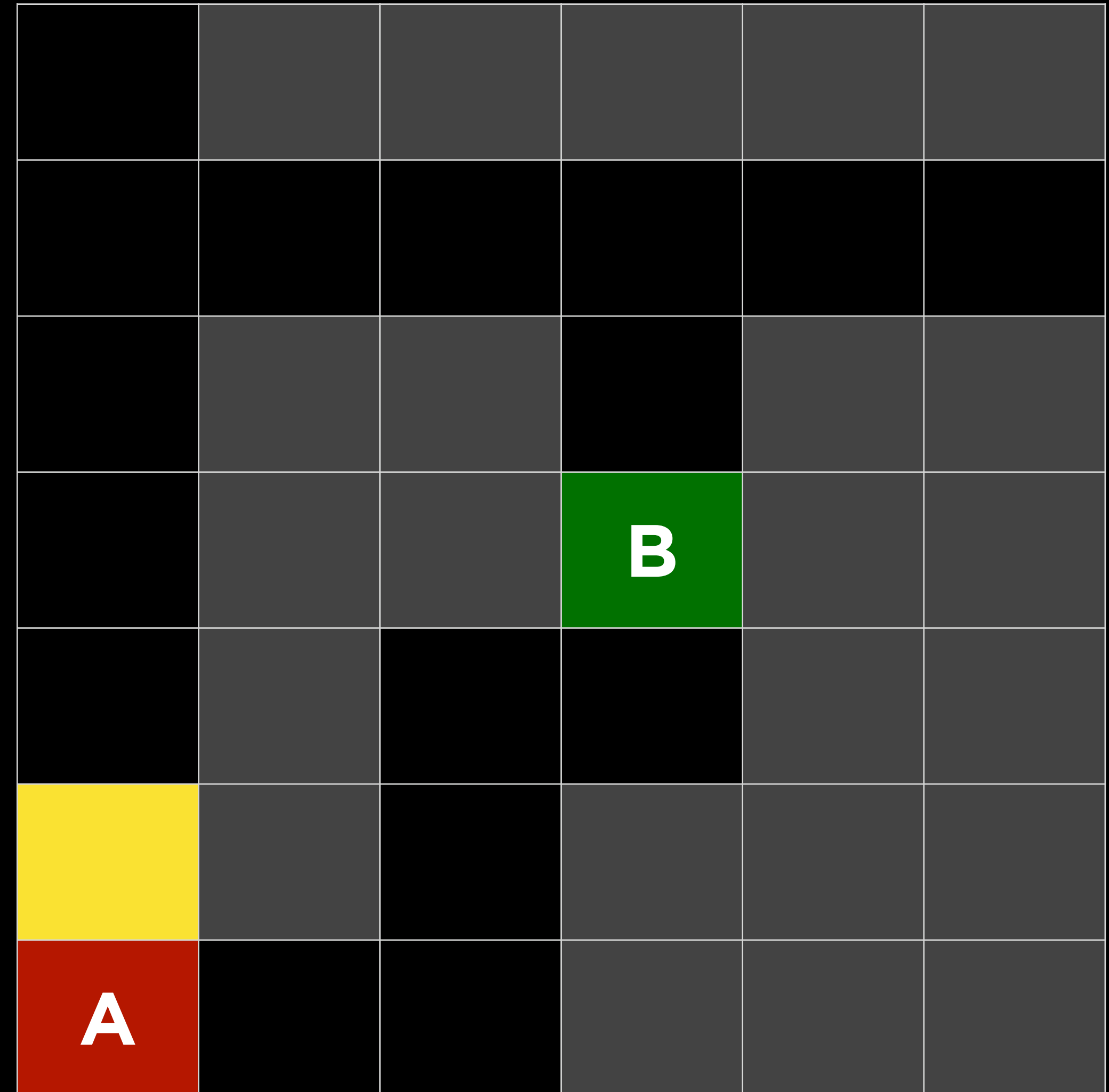


# Breadth-First Search

# Breadth-First Search

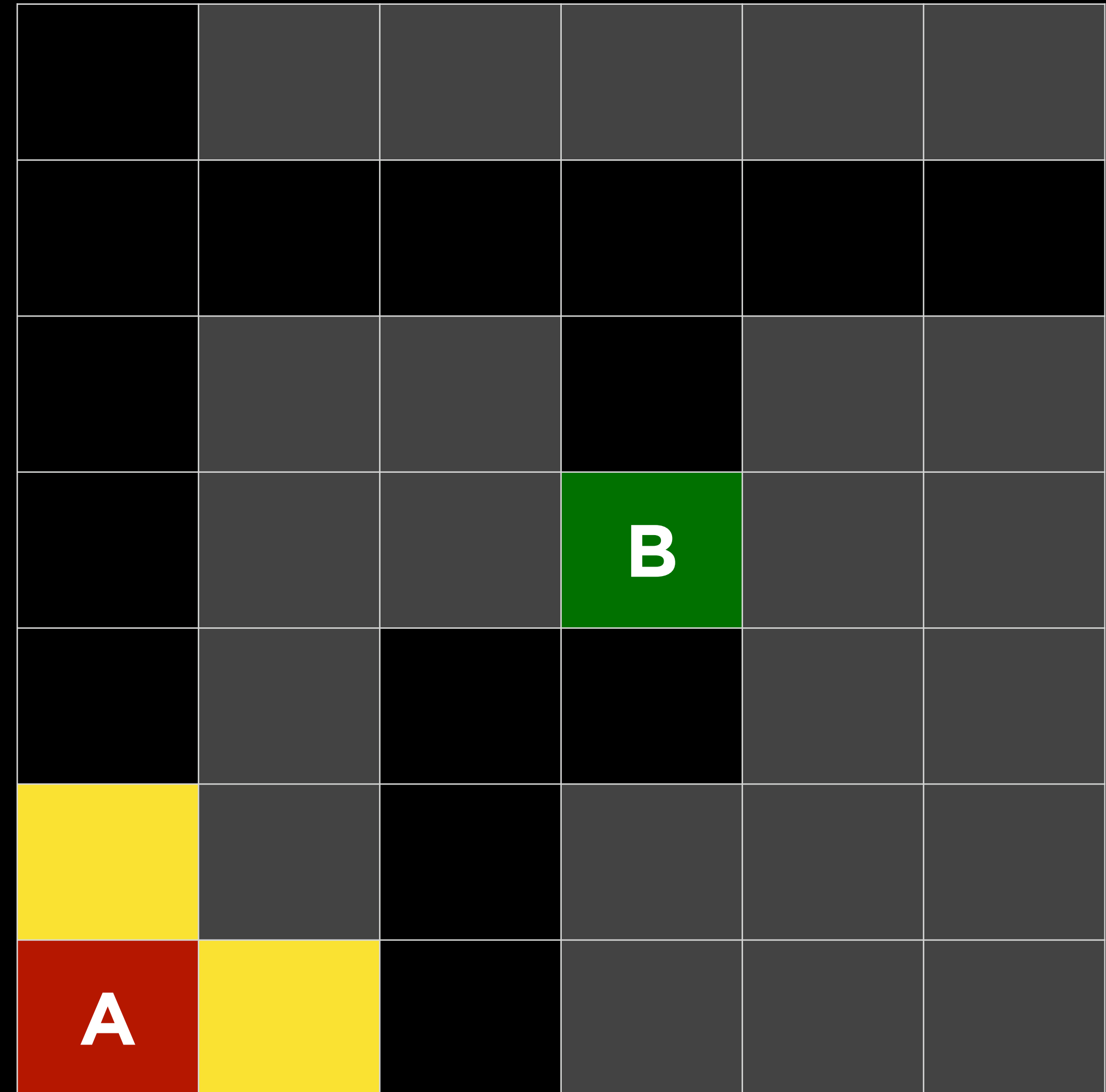


# Breadth-First Search

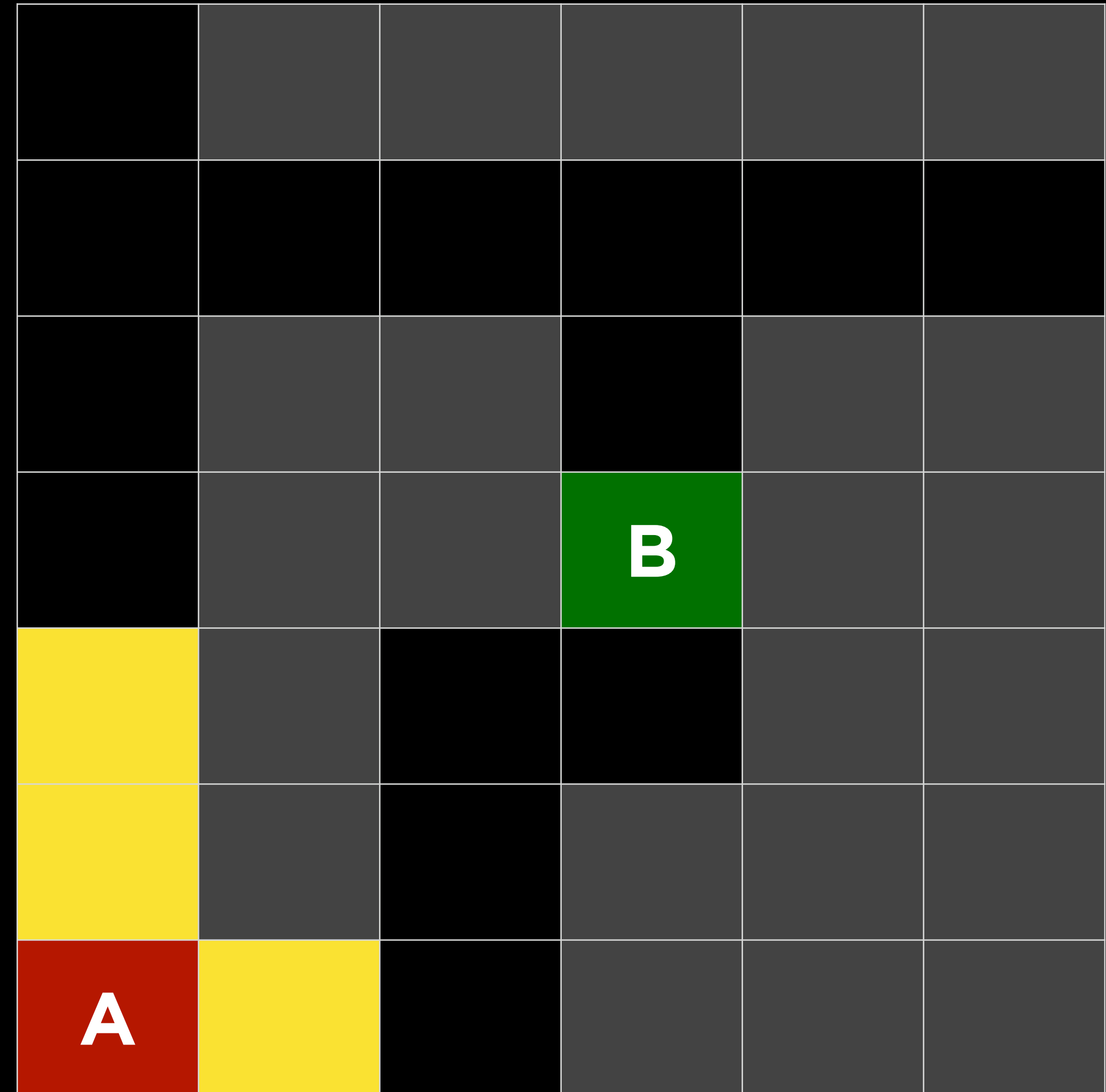




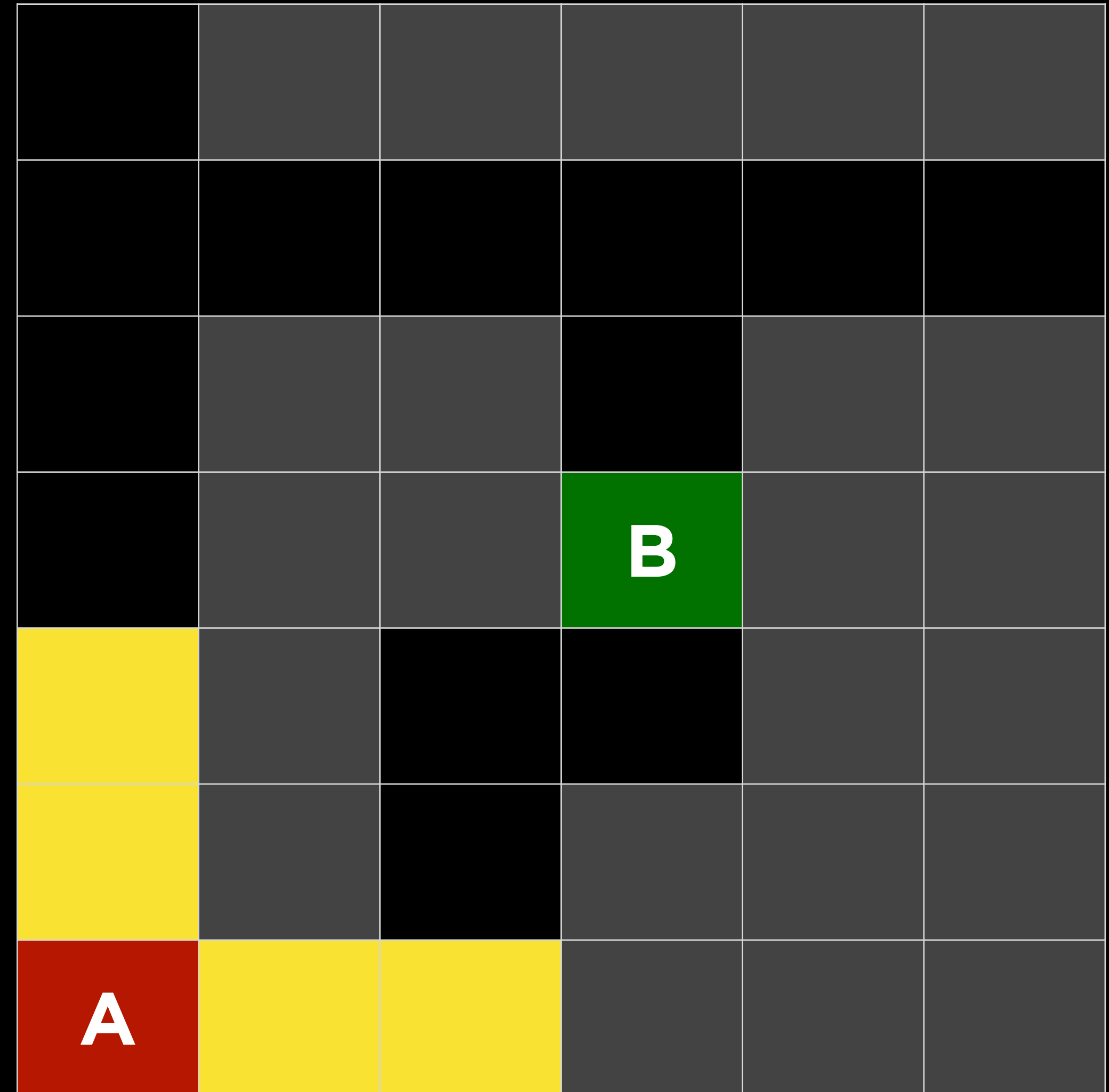
# Breadth-First Search



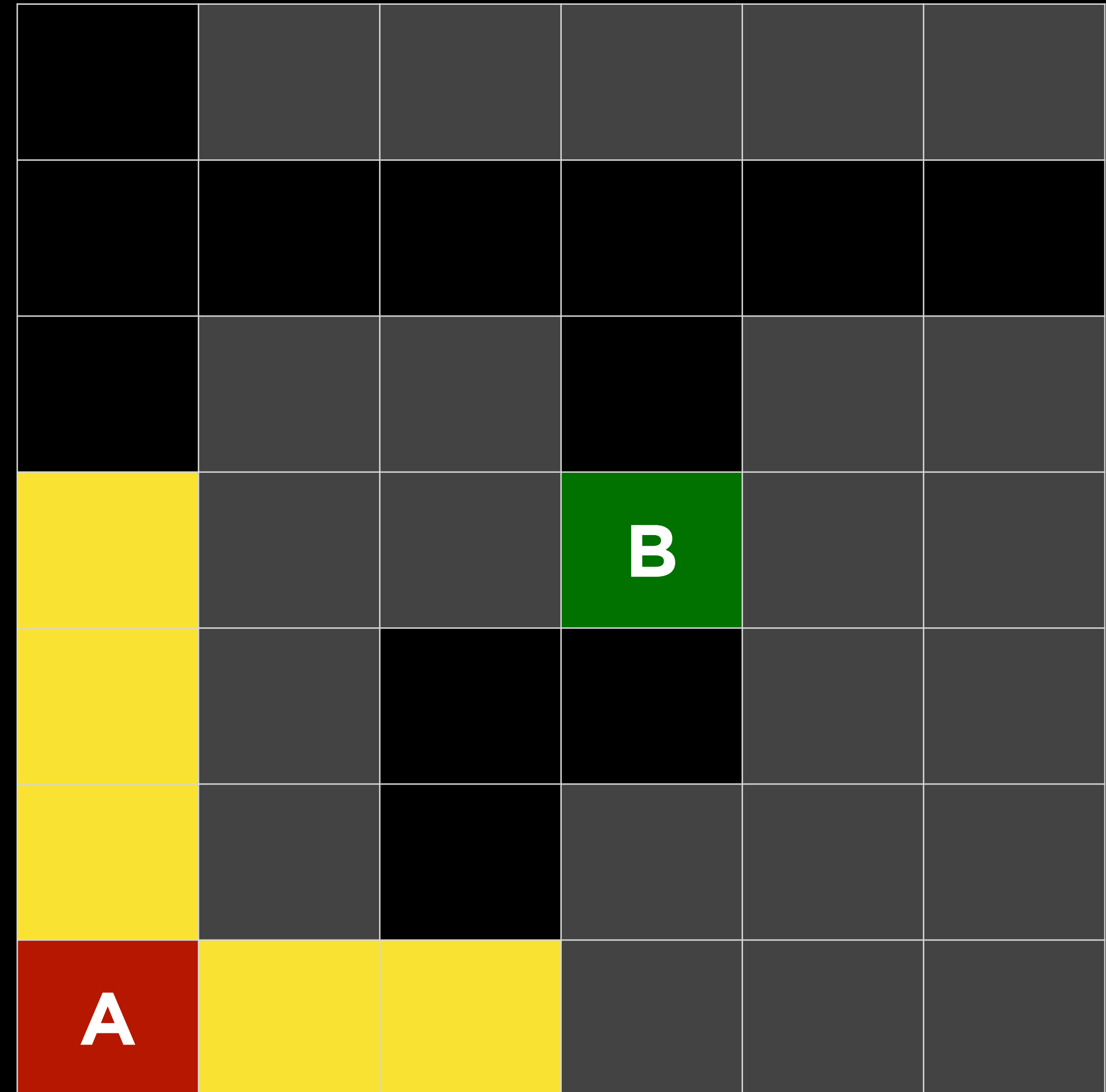
# Breadth-First Search



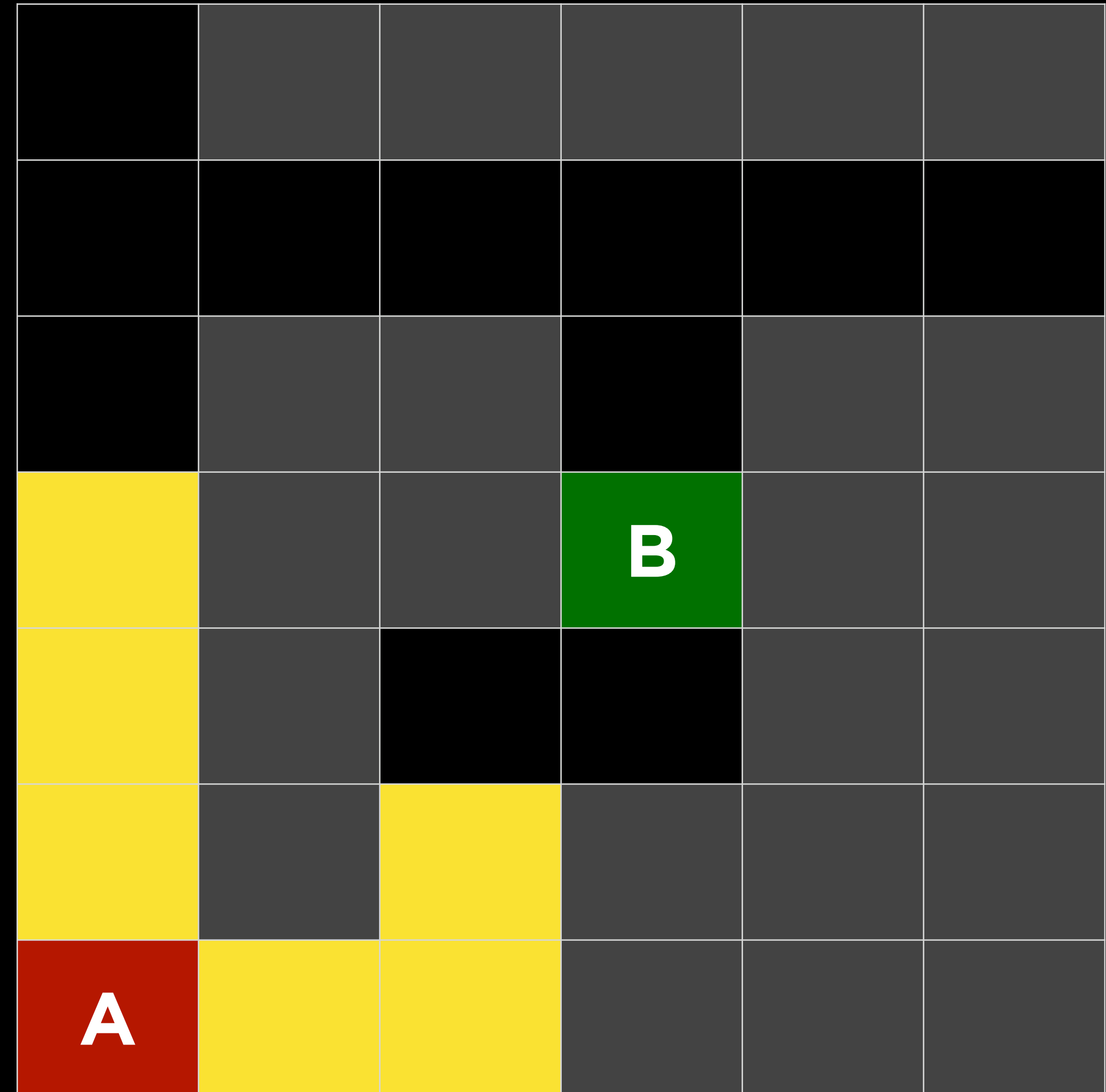
# Breadth-First Search



# Breadth-First Search

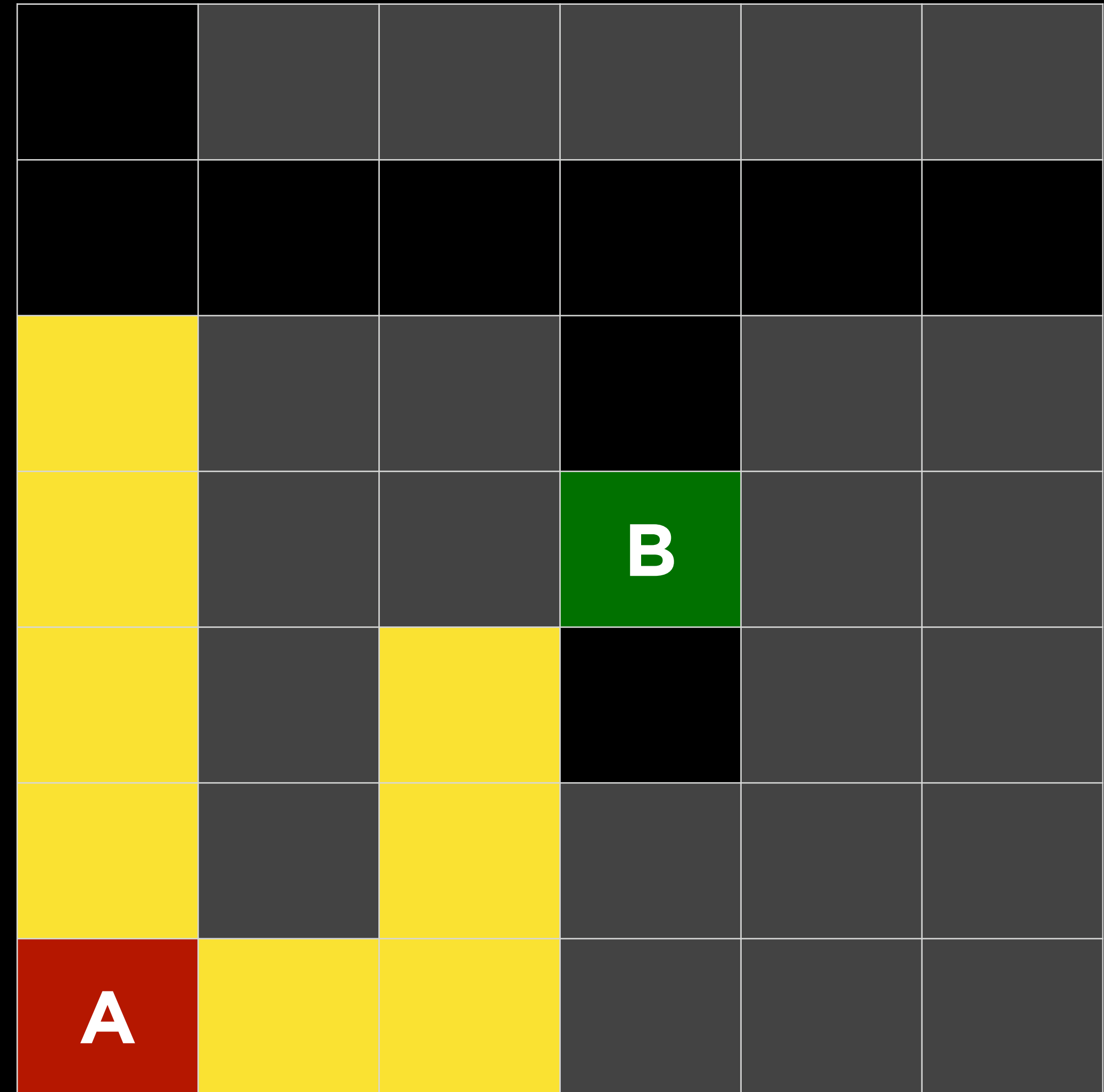


# Breadth-First Search

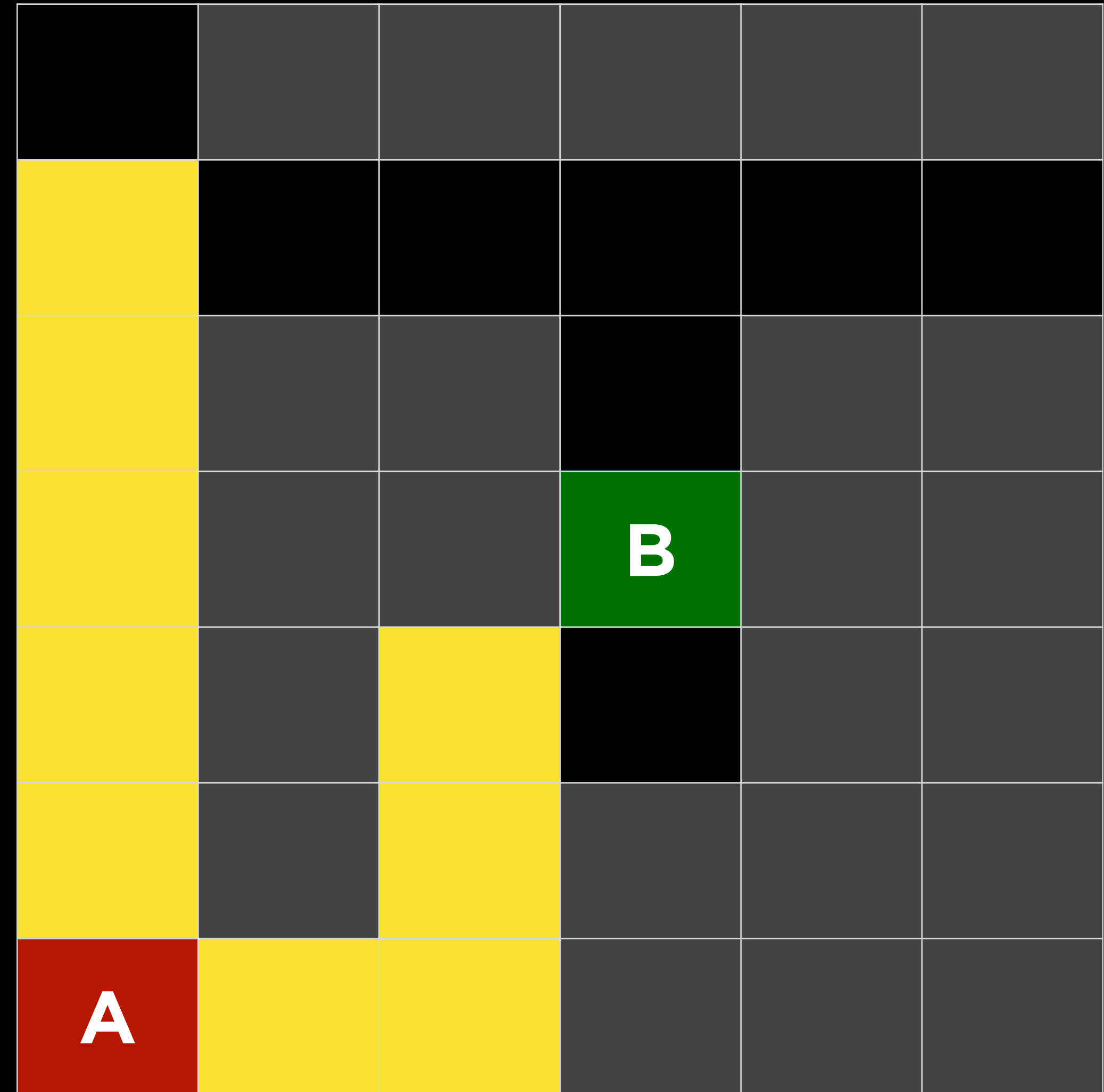




# Breadth-First Search



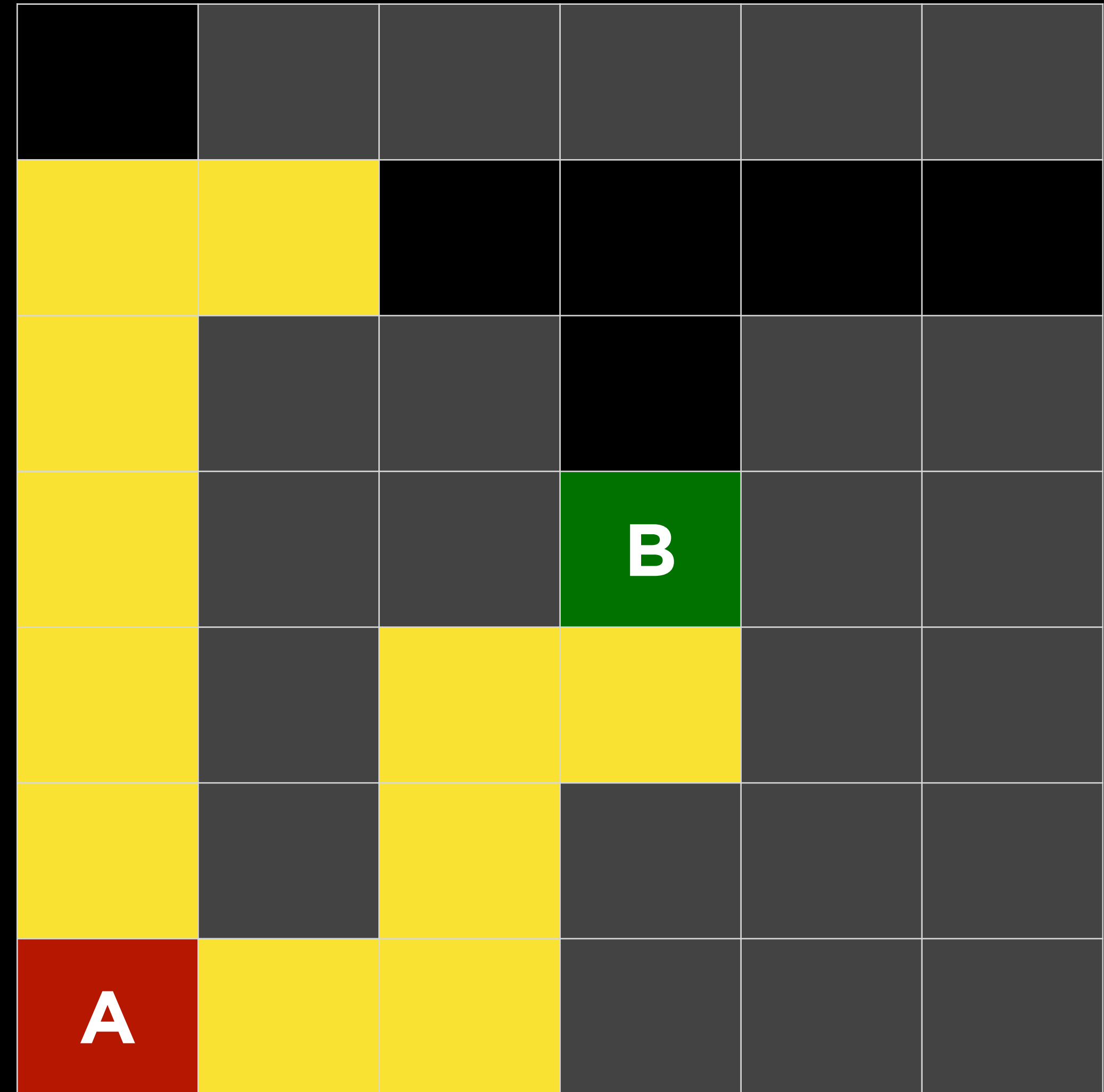
# Breadth-First Search







# Breadth-First Search









**uninformed search**

# **informed search**

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









# Greedy Best-First Search

# Greedy Best-First Search

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

# Greedy Best-First Search

11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
			13			10					
<b>A</b>	16	15	14			11	10	9	8	7	6

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	13			10		8		6			3
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<b>A</b>	16	15	14			11	10	9	8	7	6



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	13			10		8		6			3
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<b>A</b>	16	15	14			11	10	9	8	7	6

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<b>A</b>	16	15	14			11	10	9	8	7	6

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	13			10		8		6			3
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<b>A</b>	16	15	14			11	10	9	8	7	6

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<b>A</b>	16	15	14			11	10	9	8	7	6

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11		9		7				3	2		<b>B</b>
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13	12	11		9		7	6	5			2
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			13			10					
<b>A</b>	16	15	14			11	10	9	8	7	6

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11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

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11		9		7				3	2		<b>B</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
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<b>A</b>	16	15	14			11	10	9	8	7	6

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	13			10		8		6			3
	14	13	12	11		9		7	6	5	4
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<b>A</b>	16	15	14			11	10	9	8	7	6

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	14	13	12	11		9		7	6	5	4
			13			10					
<b>A</b>	16	15	14			11	10	9	8	7	6



# Greedy Best-First Search

11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

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

# Greedy Best-First Search

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

# Greedy Best-First Search

11		9		7				3	2		<b>B</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					
<b>A</b>	16	15	14			11	10	9	8	7	6

# Greedy Best-First Search

	10	9	8	7	6	5	4	3	2	1	<b>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</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
<b>A</b>	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>B</b>
	11										1
A	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
<b>A</b>	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>B</b>
	11										1
<b>A</b>	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
<b>A</b>	16	15	14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	<b>B</b>
	11										1
<b>A</b>	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
<b>A</b>	1+16	15	14		12	11	10	9	8	7	6

# A\* Search

	10	9	8	7	6	5	4	3	2	1	<b>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</b>
	11										1
<b>A</b>	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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

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

# A\* Search

	10	9	8	7	6	5	4	3	2	1	B
	10+11										1
A	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	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>B</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
<b>A</b>	1+16	2+15	3+14		12	11	10	9	8	7	6

# A\* Search

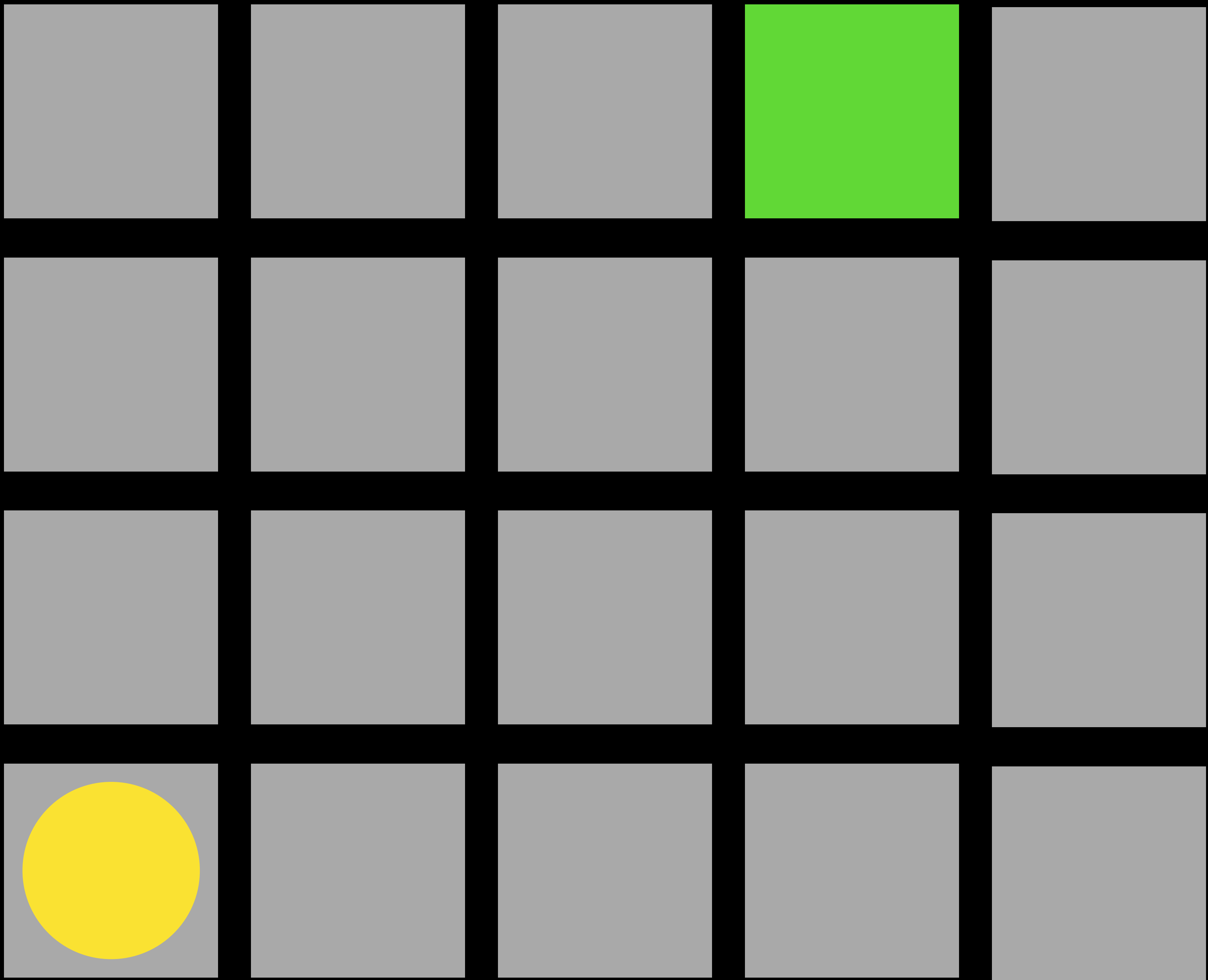
	11+10	12+9	13+8	14+7	15+6	16+5	17+4	18+3	19+2	<b>1</b>	<b>B</b>
	10+11										<b>1</b>
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		<b>2</b>
	8+13		6+11						14+5		<b>3</b>
	7+14	6+13	5+12		<b>10</b>	<b>9</b>	<b>8</b>	<b>7</b>	15+6		<b>4</b>
			4+13		<b>11</b>						<b>5</b>
<b>A</b>	1+16	2+15	3+14		<b>12</b>	<b>11</b>	<b>10</b>	<b>9</b>	<b>8</b>	<b>7</b>	<b>6</b>

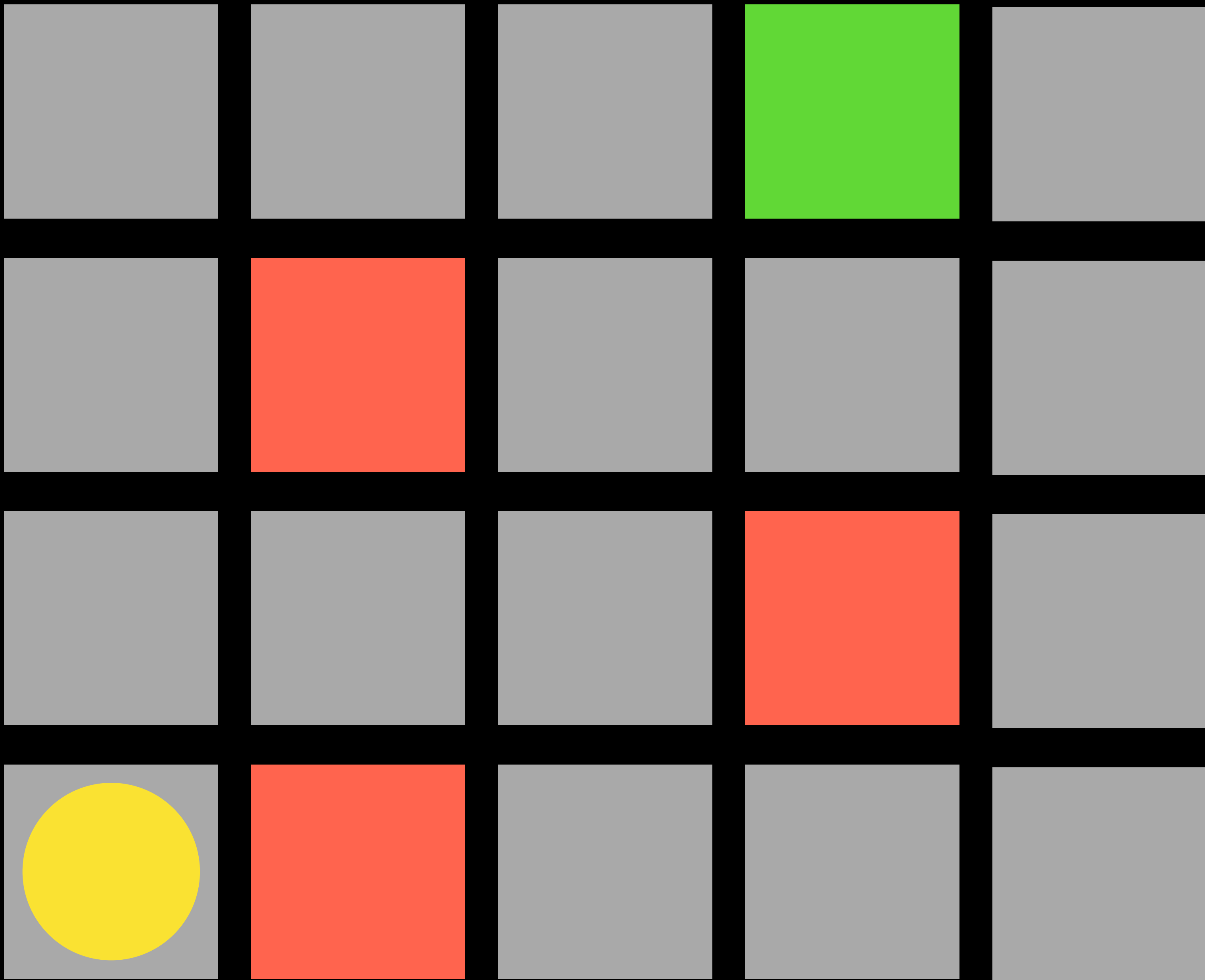


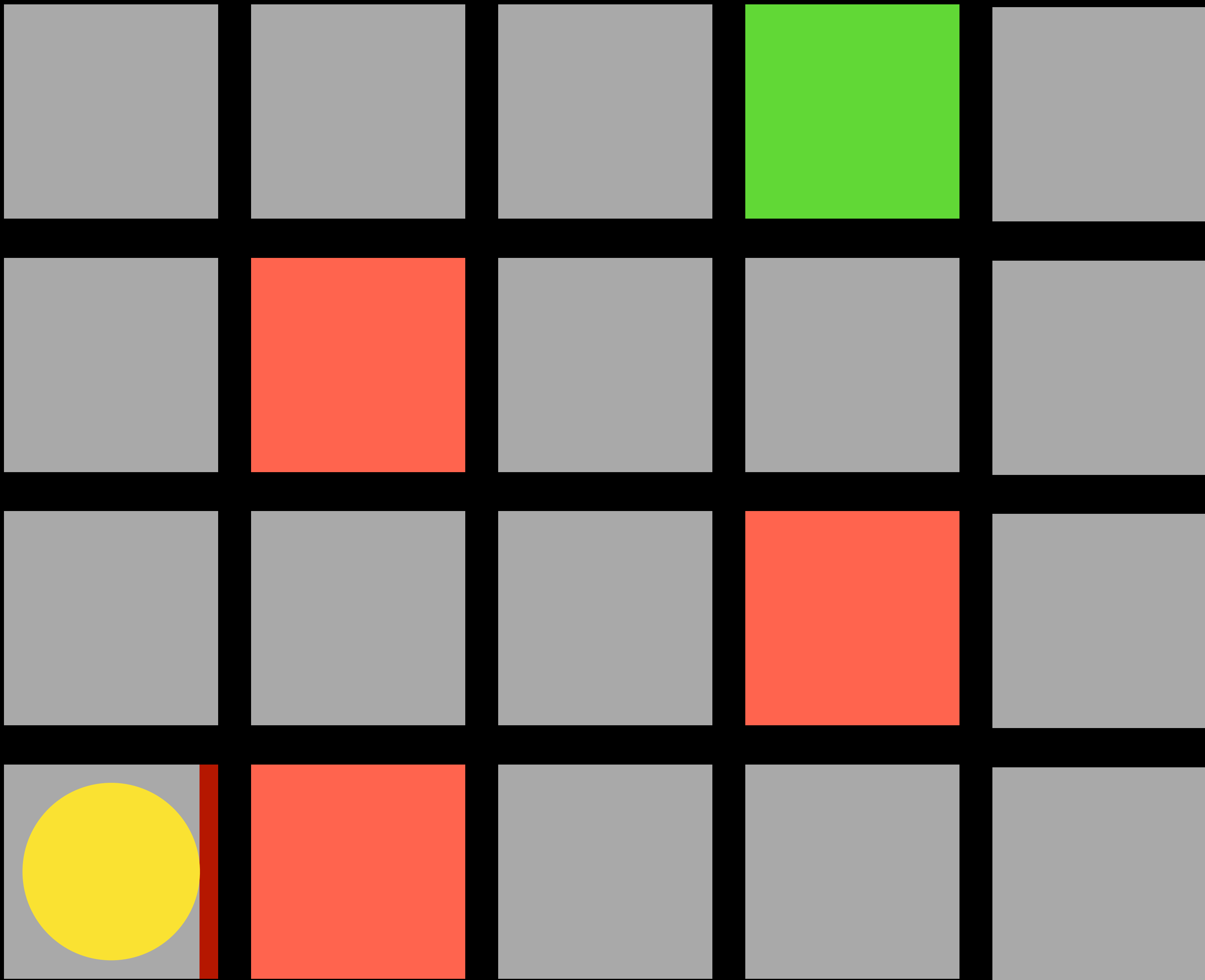
# A\* Search

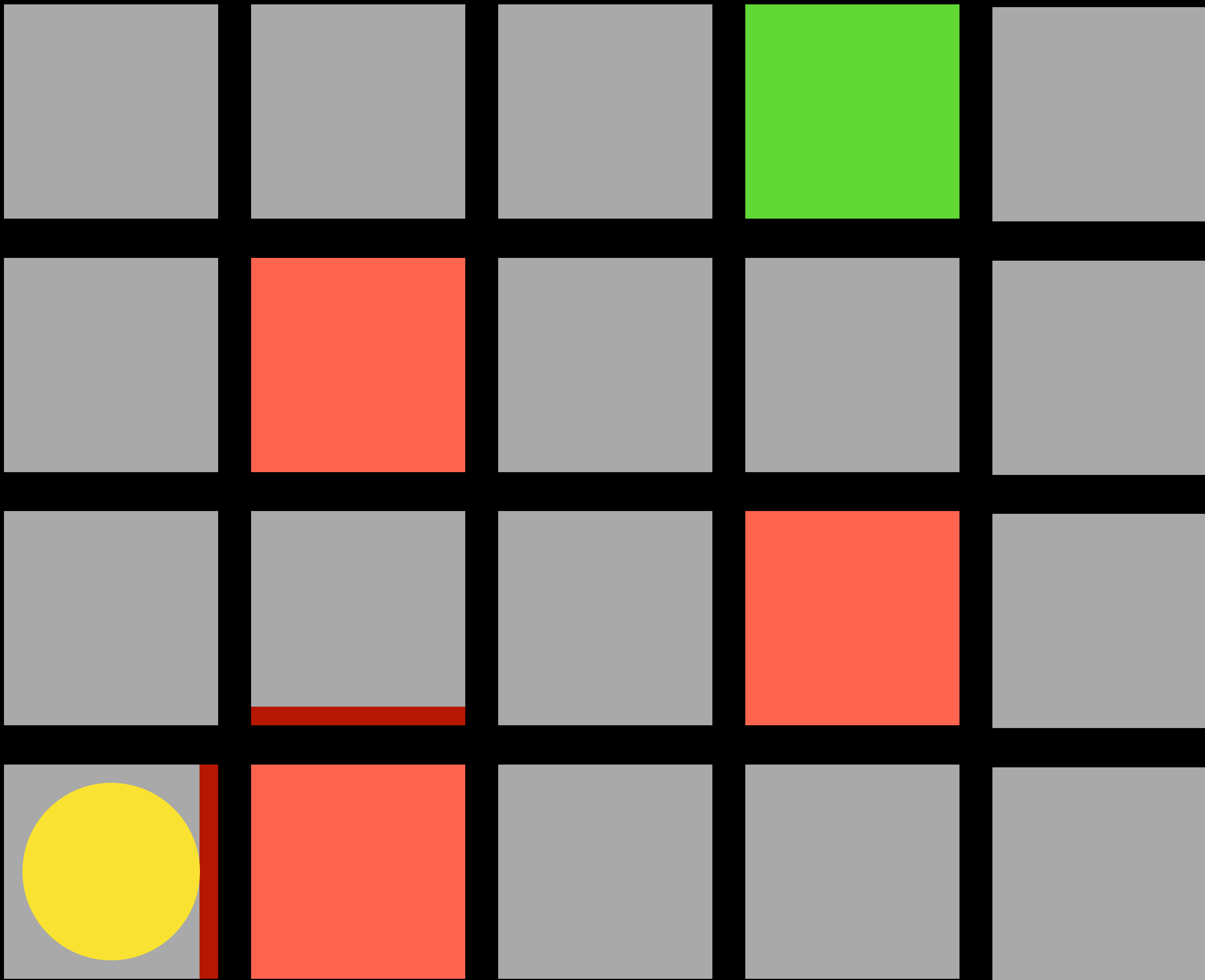
	11+10	12+9	13+8	14+7	15+6	16+5	17+4	18+3	19+2	20+1	<b>B</b>
	10+11										<b>1</b>
	9+12		7+10	8+9	9+8	10+7	11+6	12+5	13+4		<b>2</b>
	8+13		6+11						14+5		<b>3</b>
	7+14	6+13	5+12		<b>10</b>	<b>9</b>	<b>8</b>	<b>7</b>	15+6		<b>4</b>
			4+13		<b>11</b>						<b>5</b>
<b>A</b>	1+16	2+15	3+14		<b>12</b>	<b>11</b>	<b>10</b>	<b>9</b>	<b>8</b>	<b>7</b>	<b>6</b>

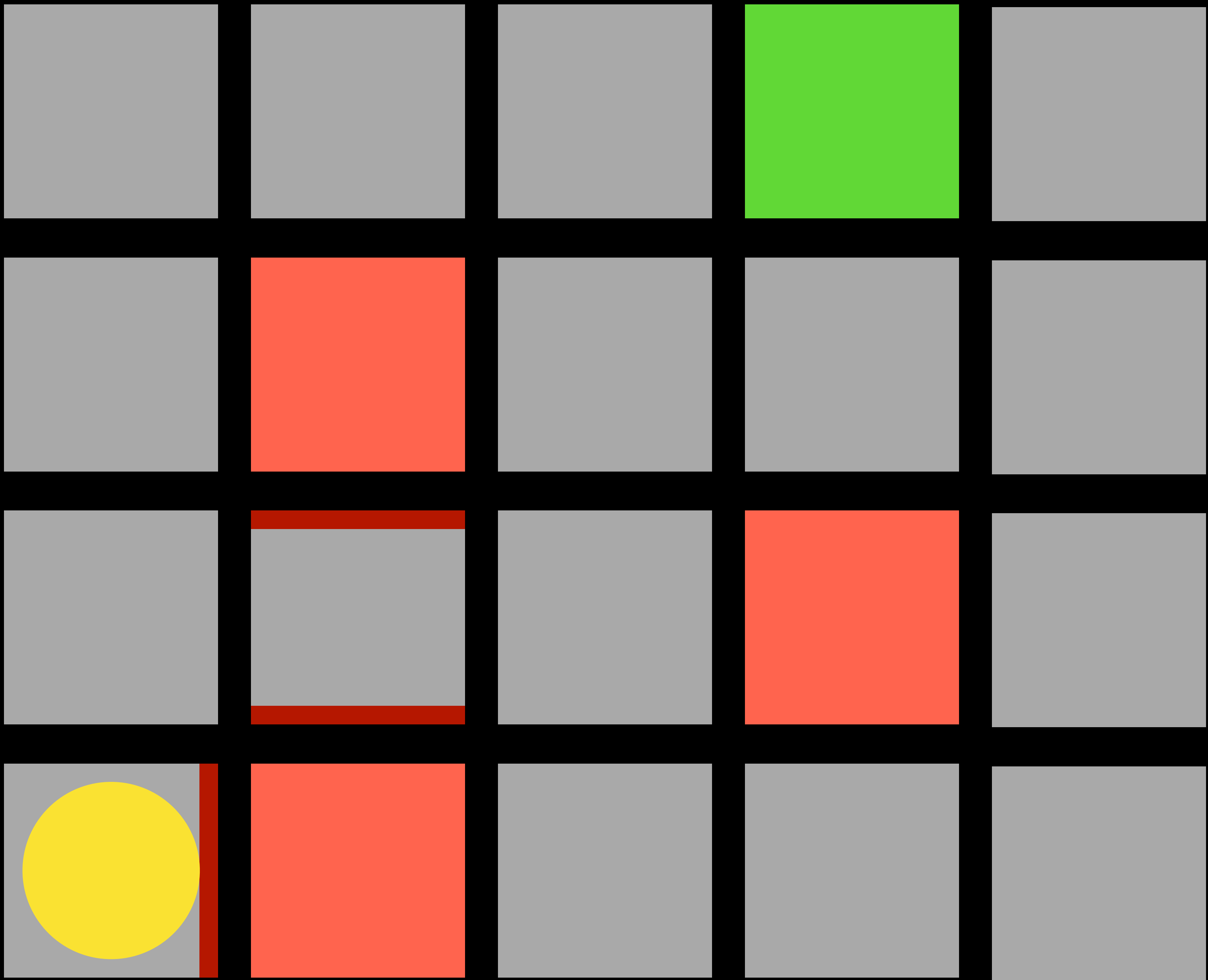
# Reinforcement Learning

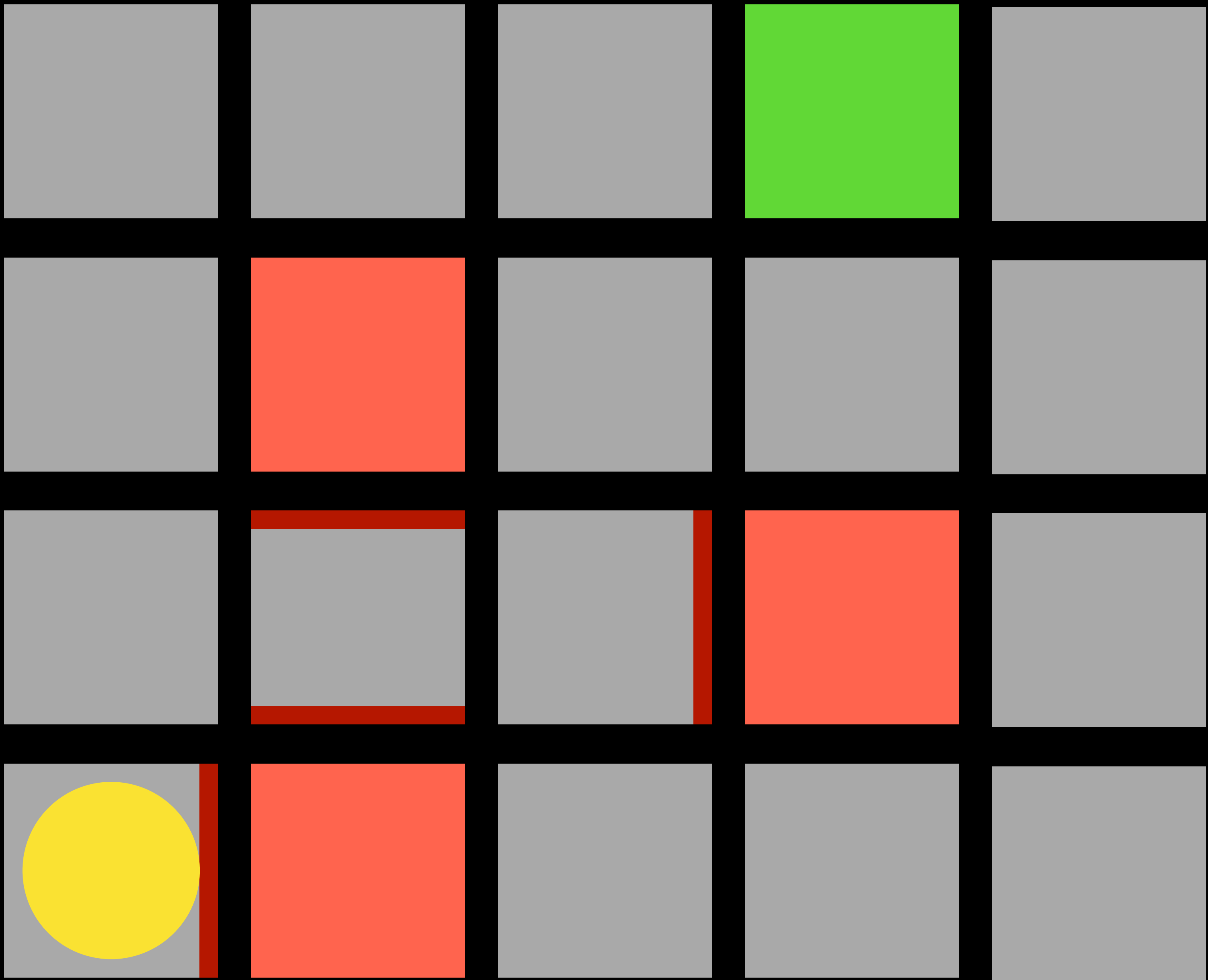




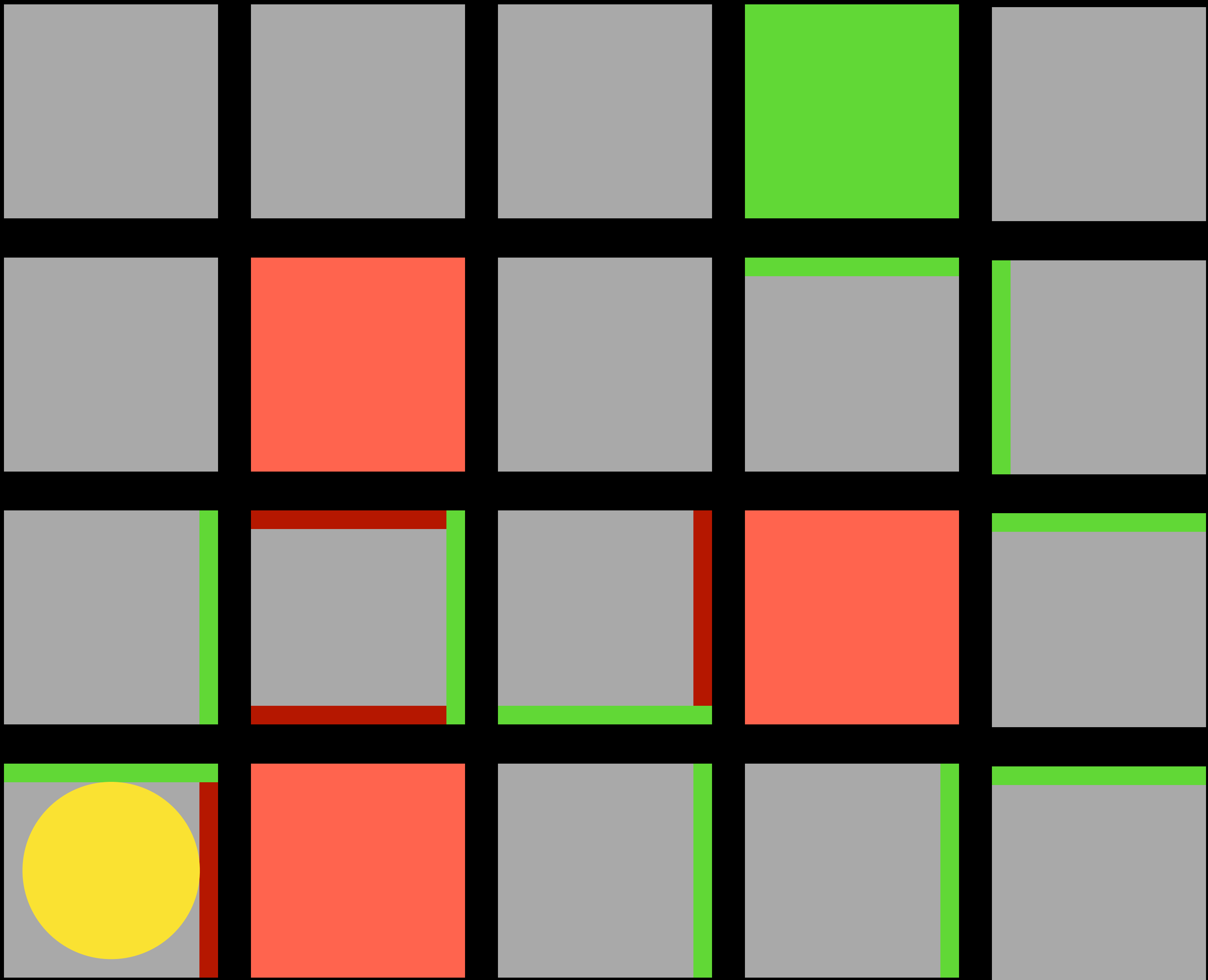


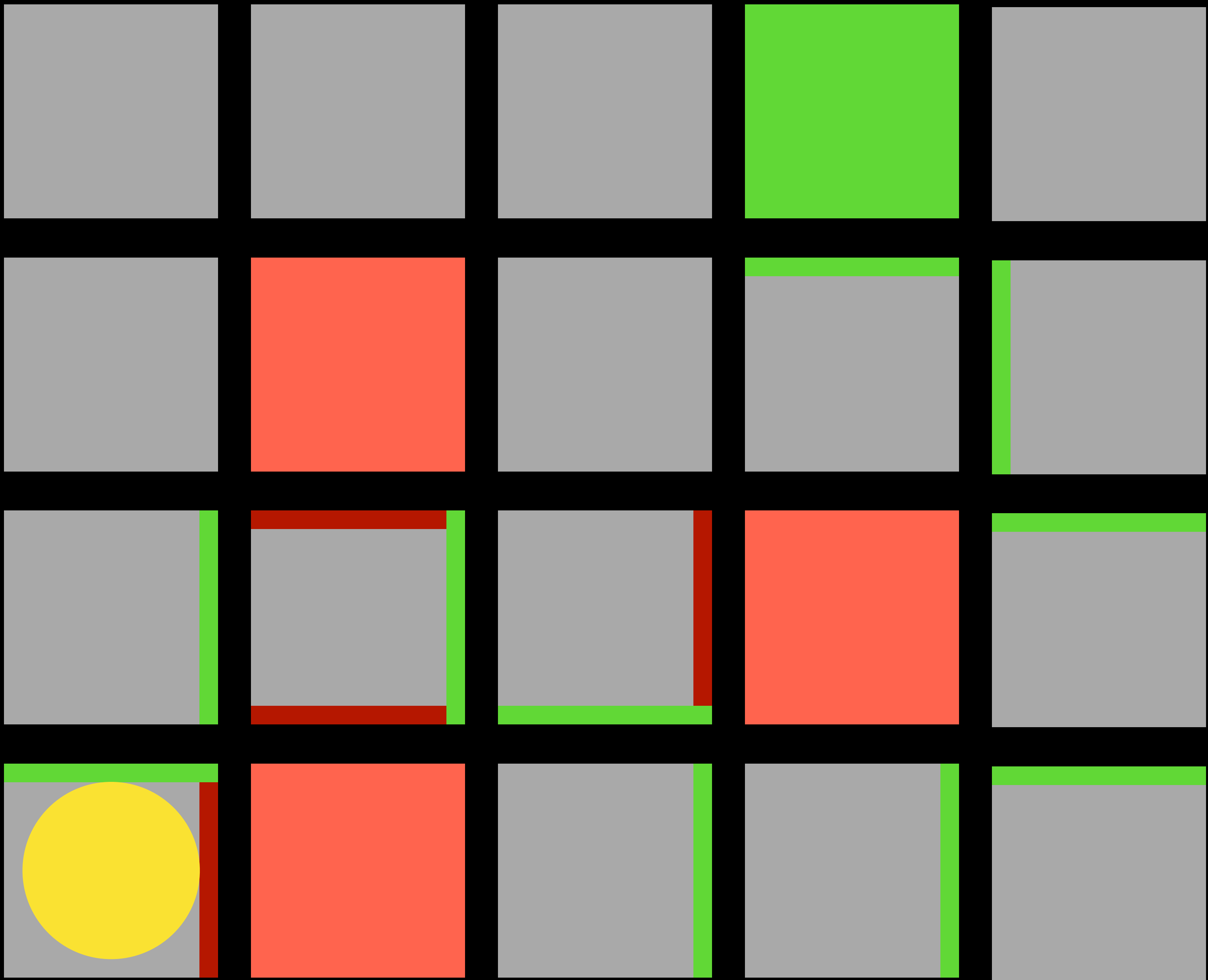












**Explore vs. Exploit**

# 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**

# 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

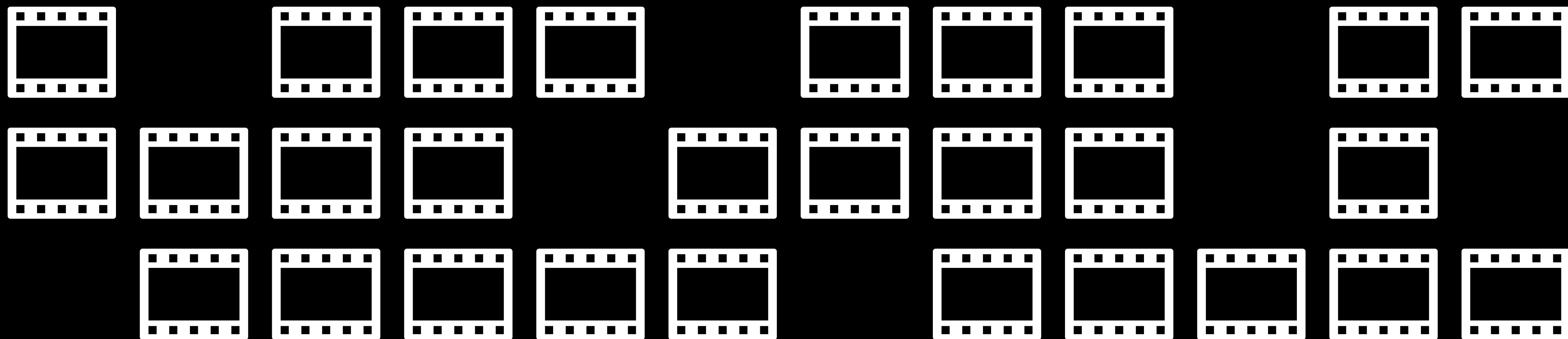
Game  
Display 1   Free Aspect   Scale 100%

Turn: -0.7932  
Engine: 0.99999  
Fitness: 9.78920

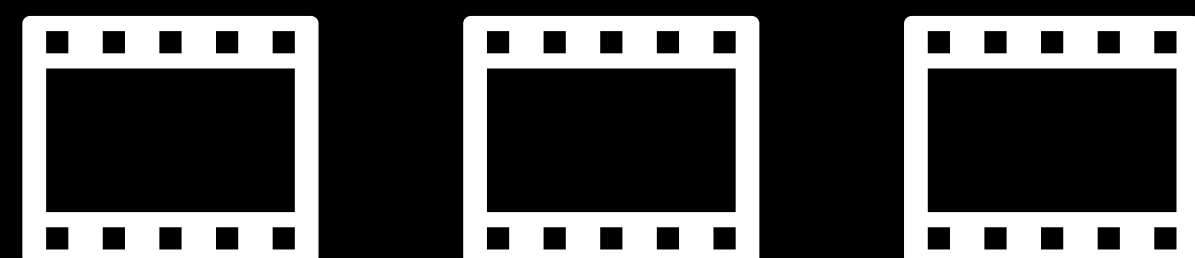
Generation: 1

Maximize on Play   Mute audio   Stats   Games

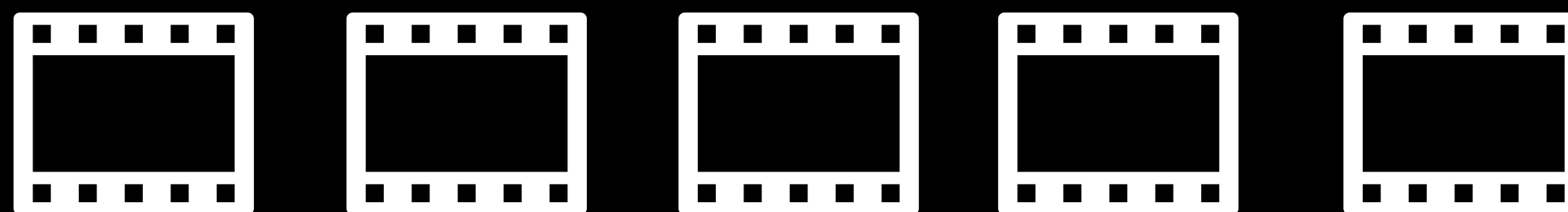


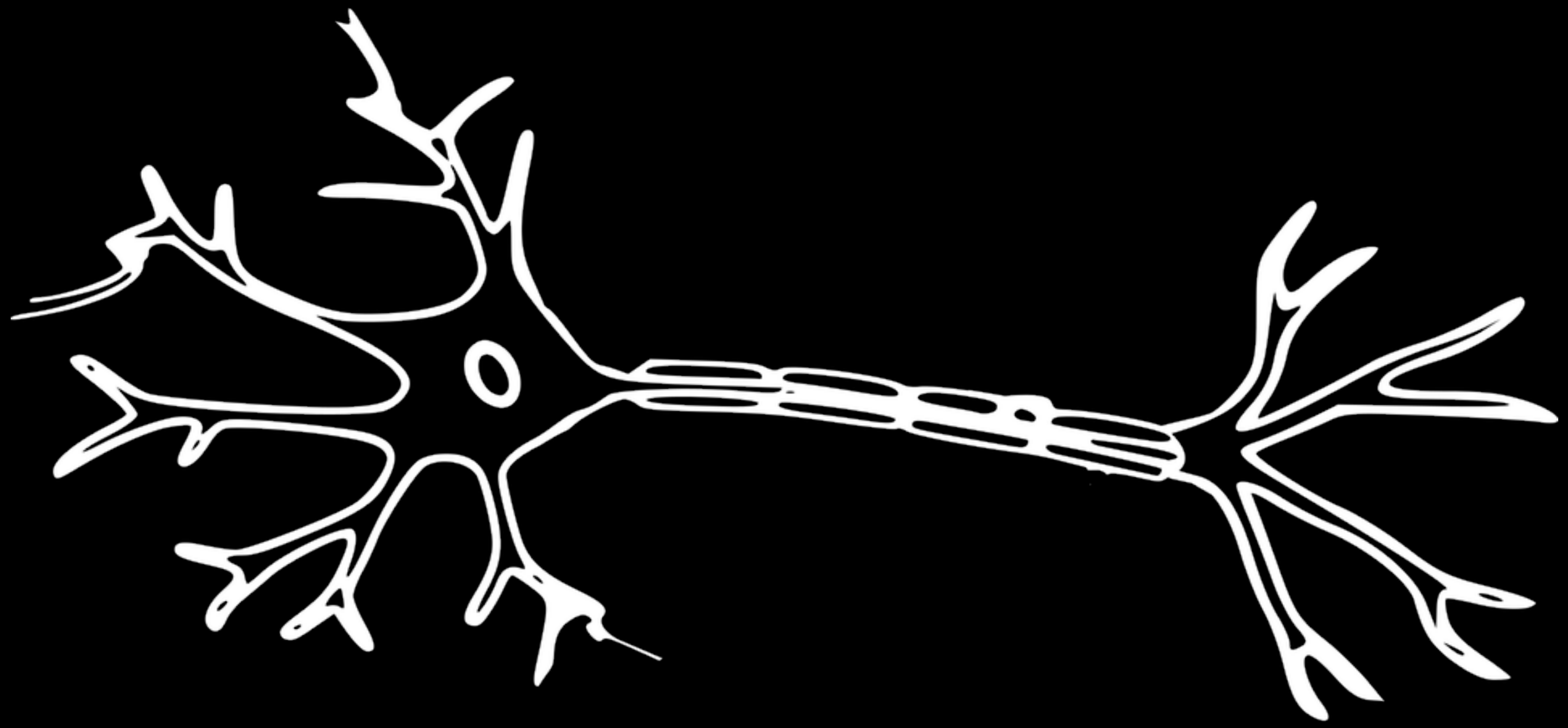


Watch History



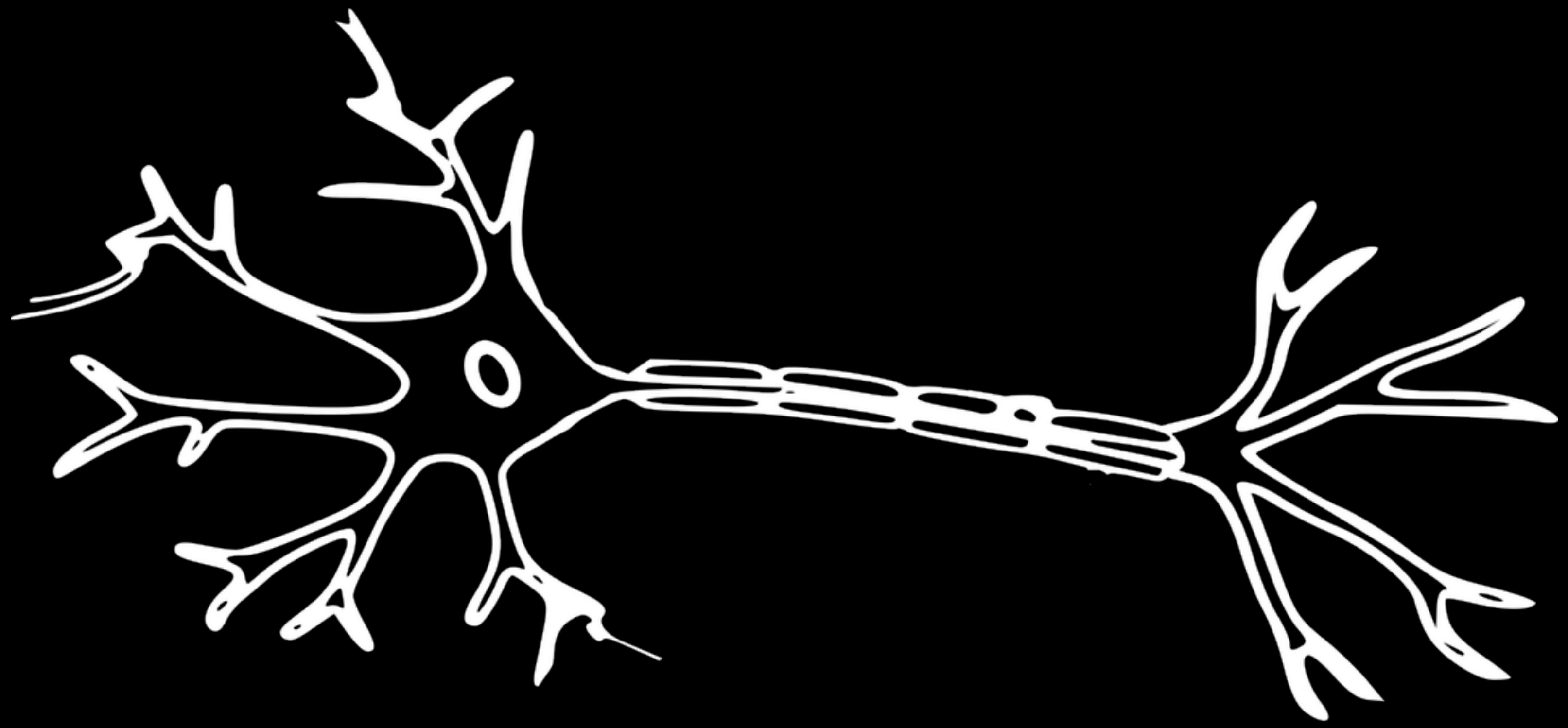
Recommended

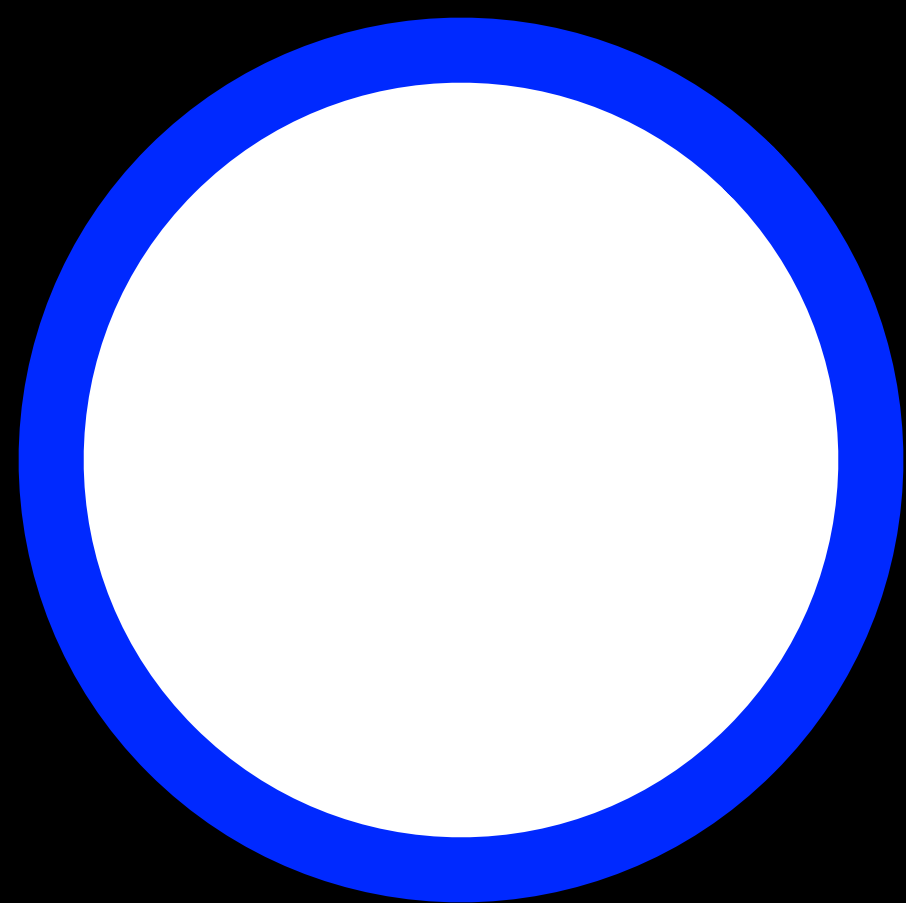


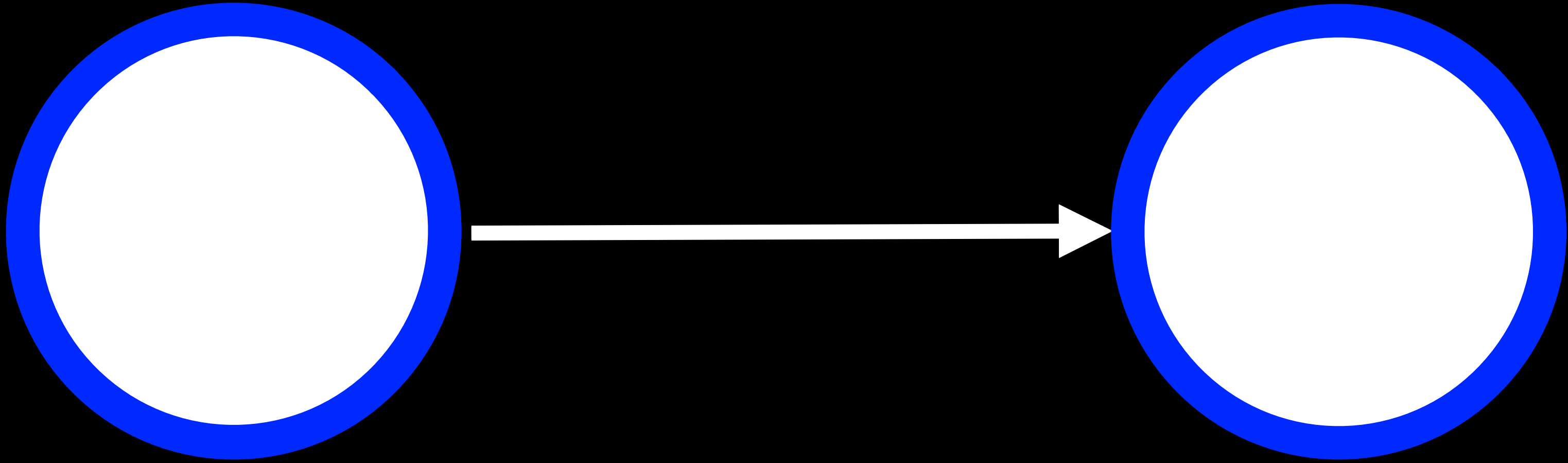


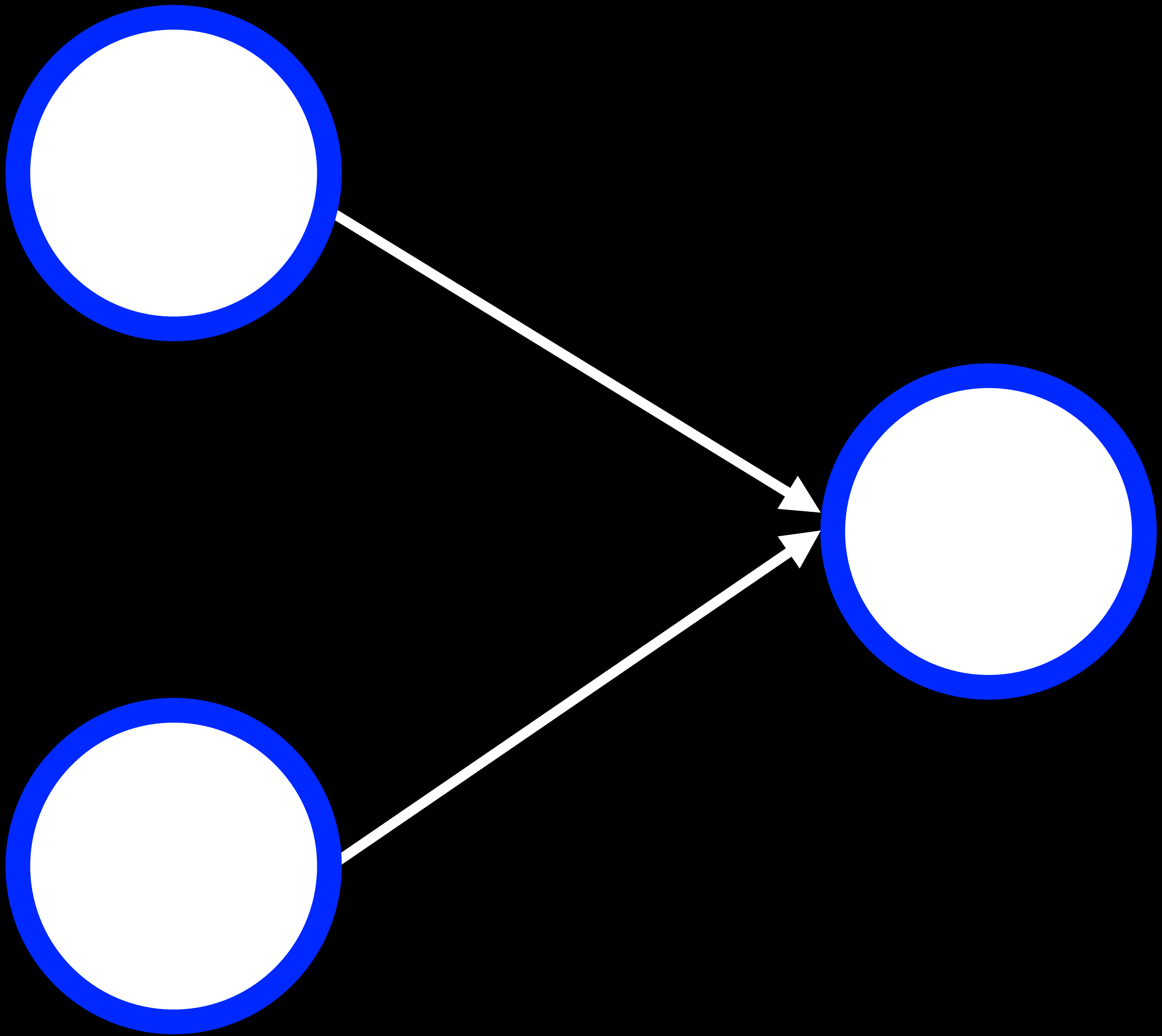


# Neural Networks

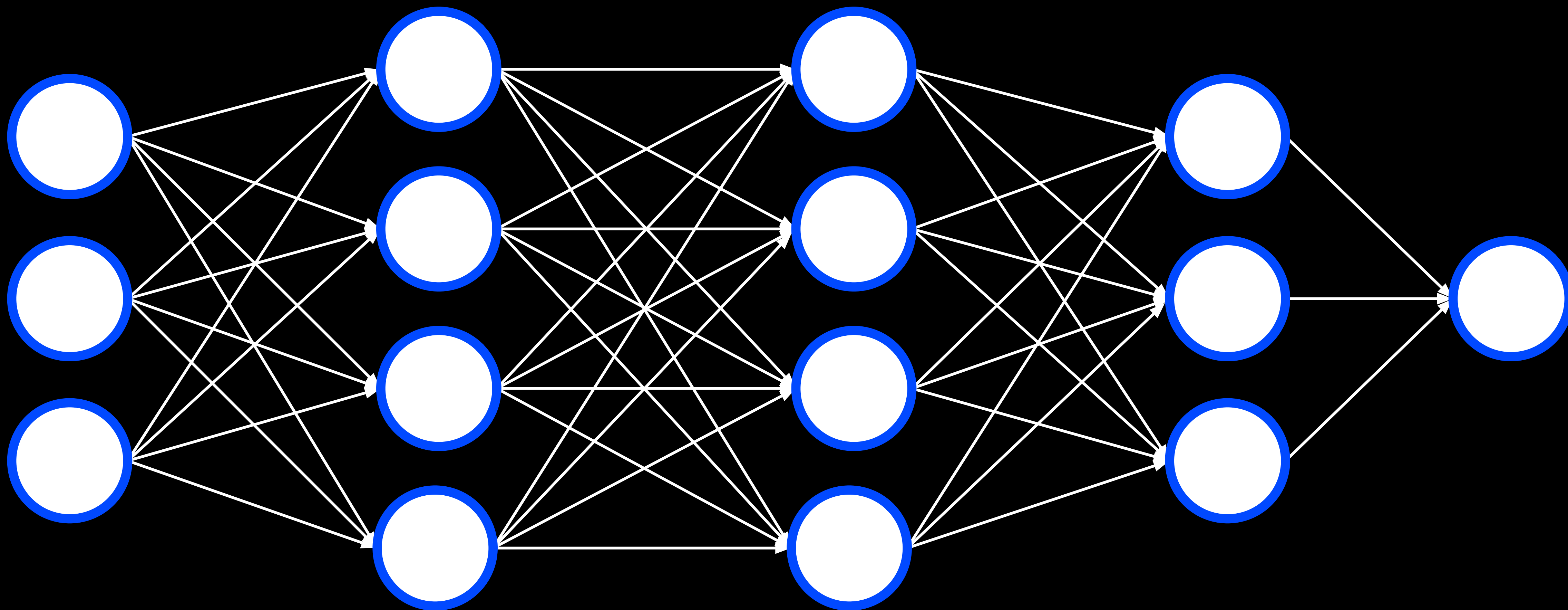


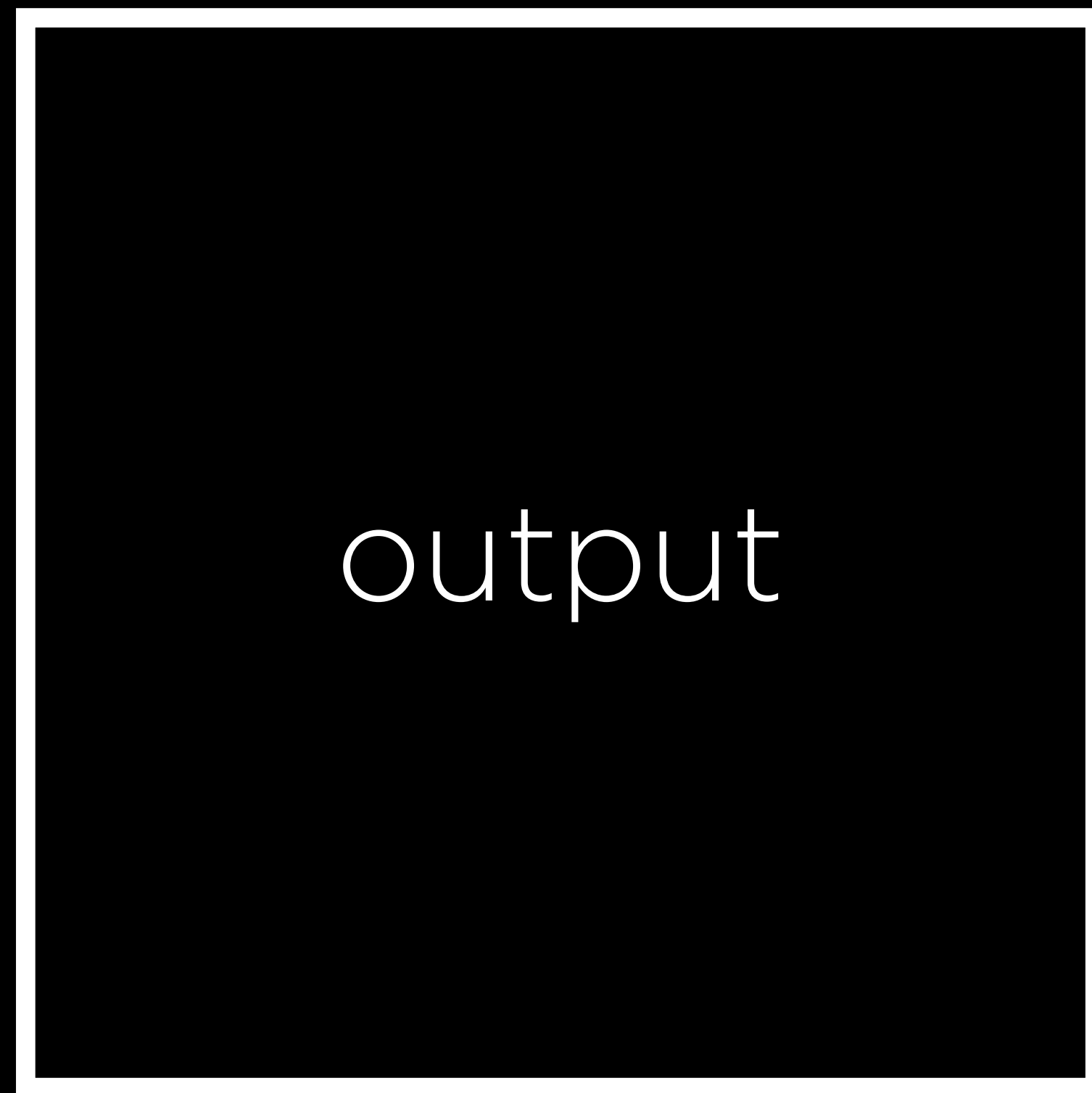
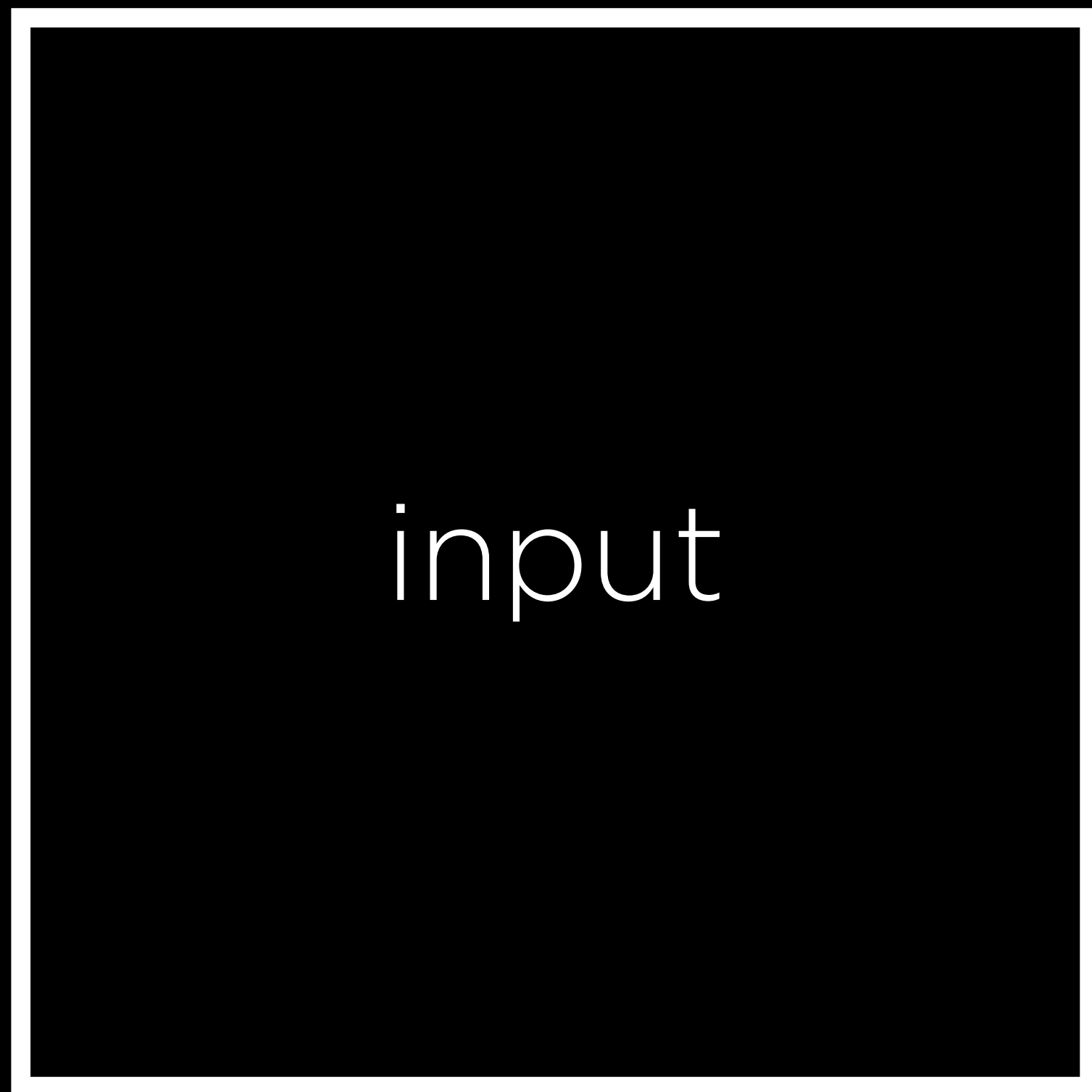


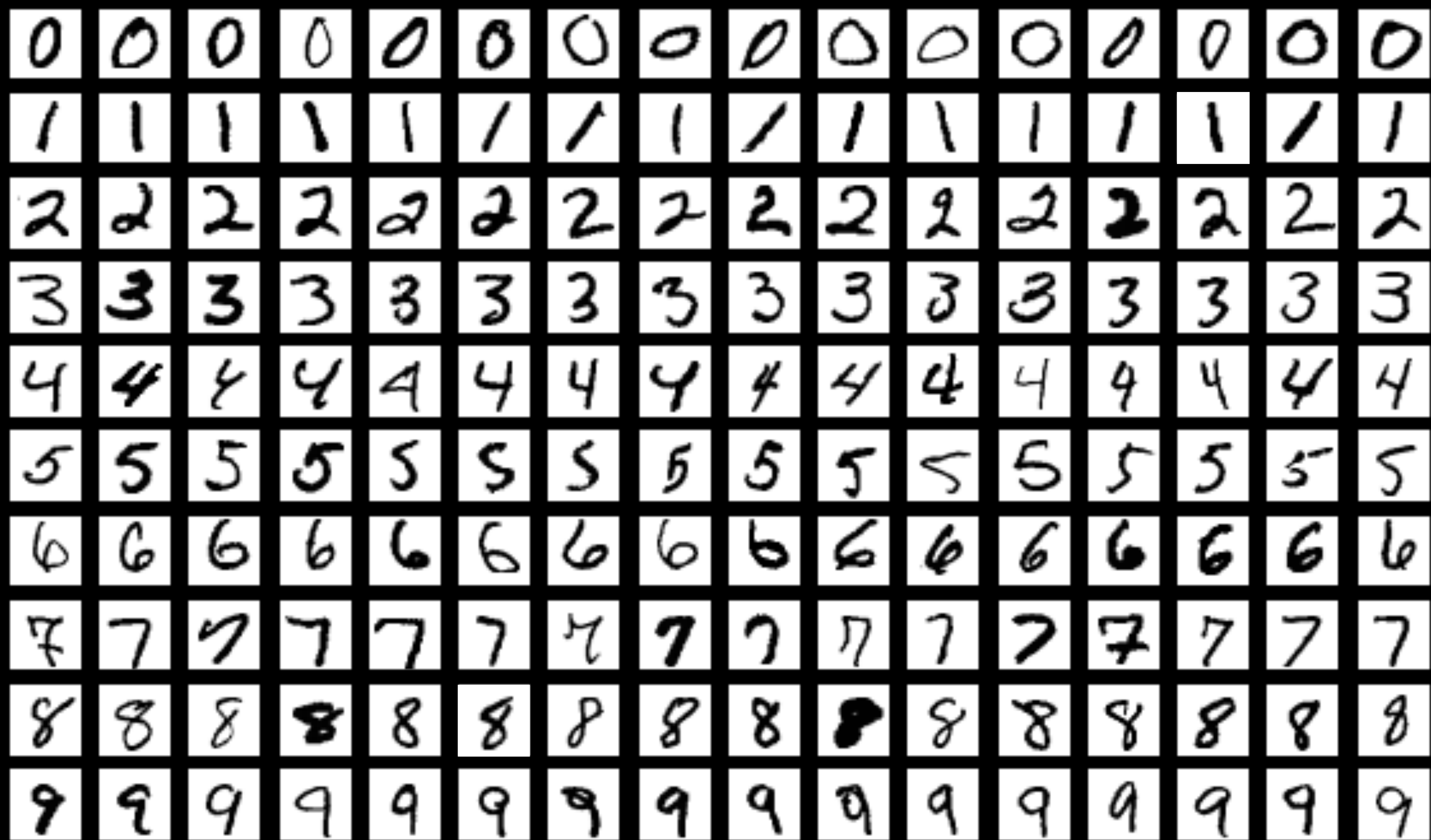


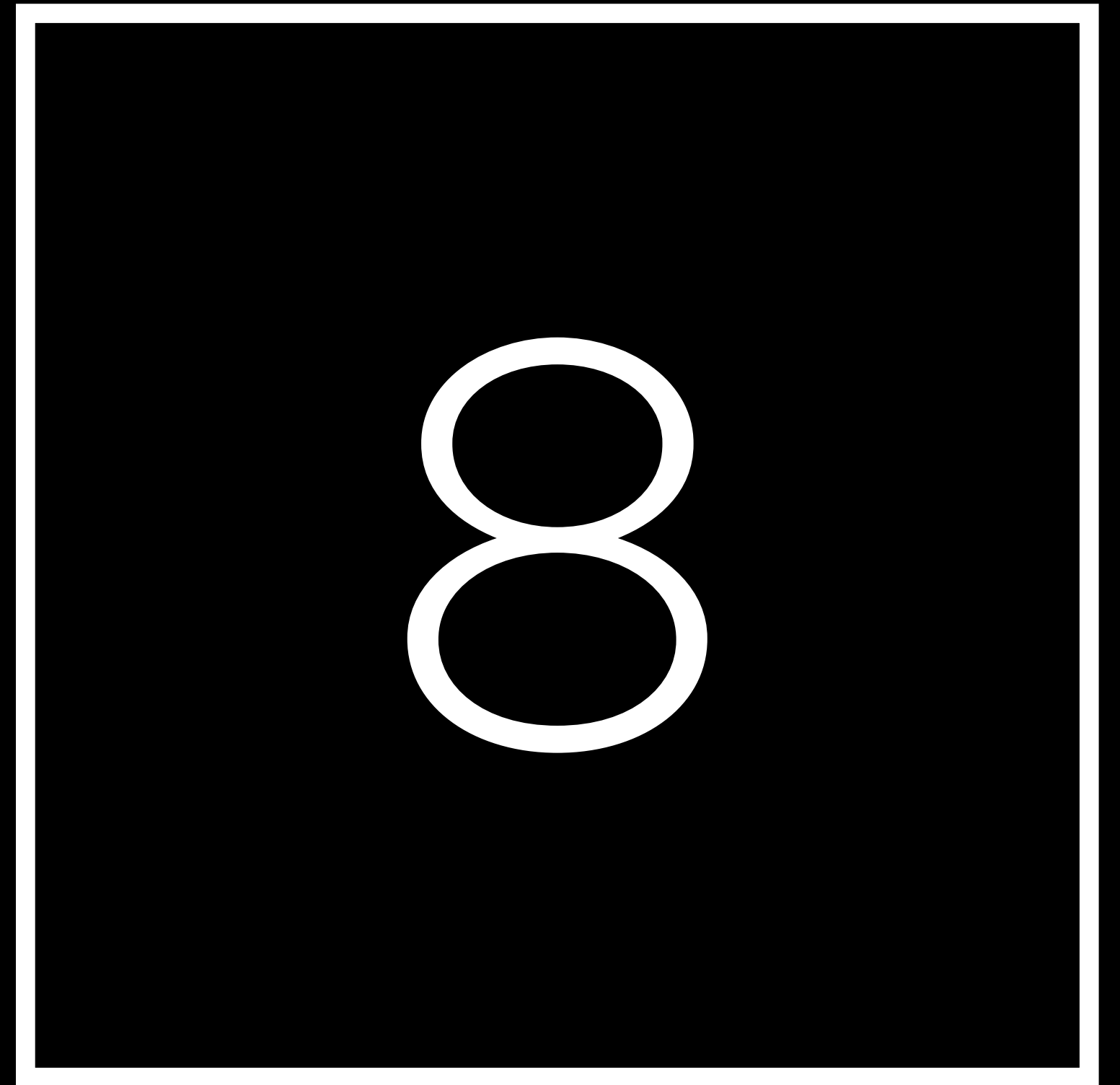


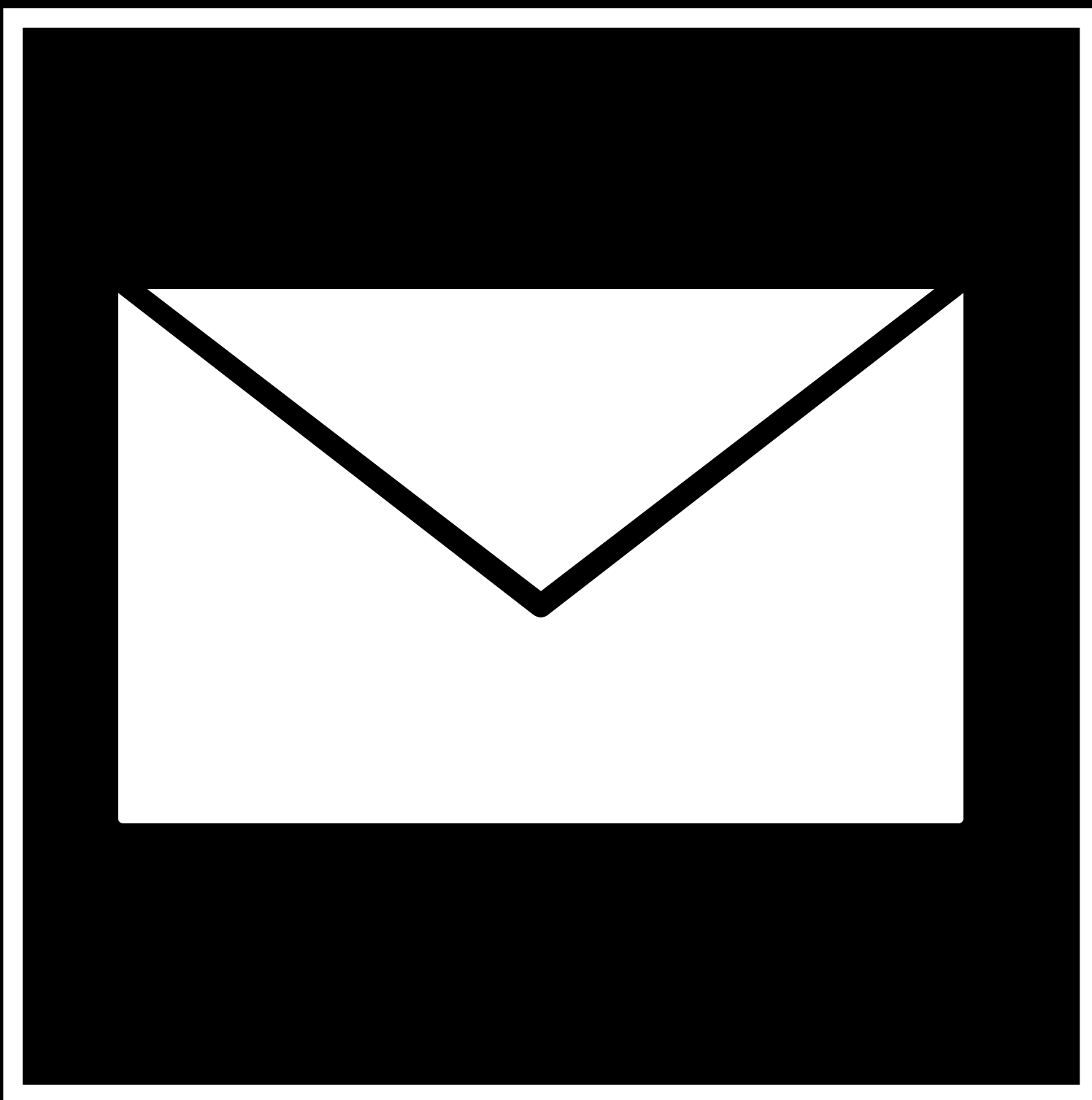












spam











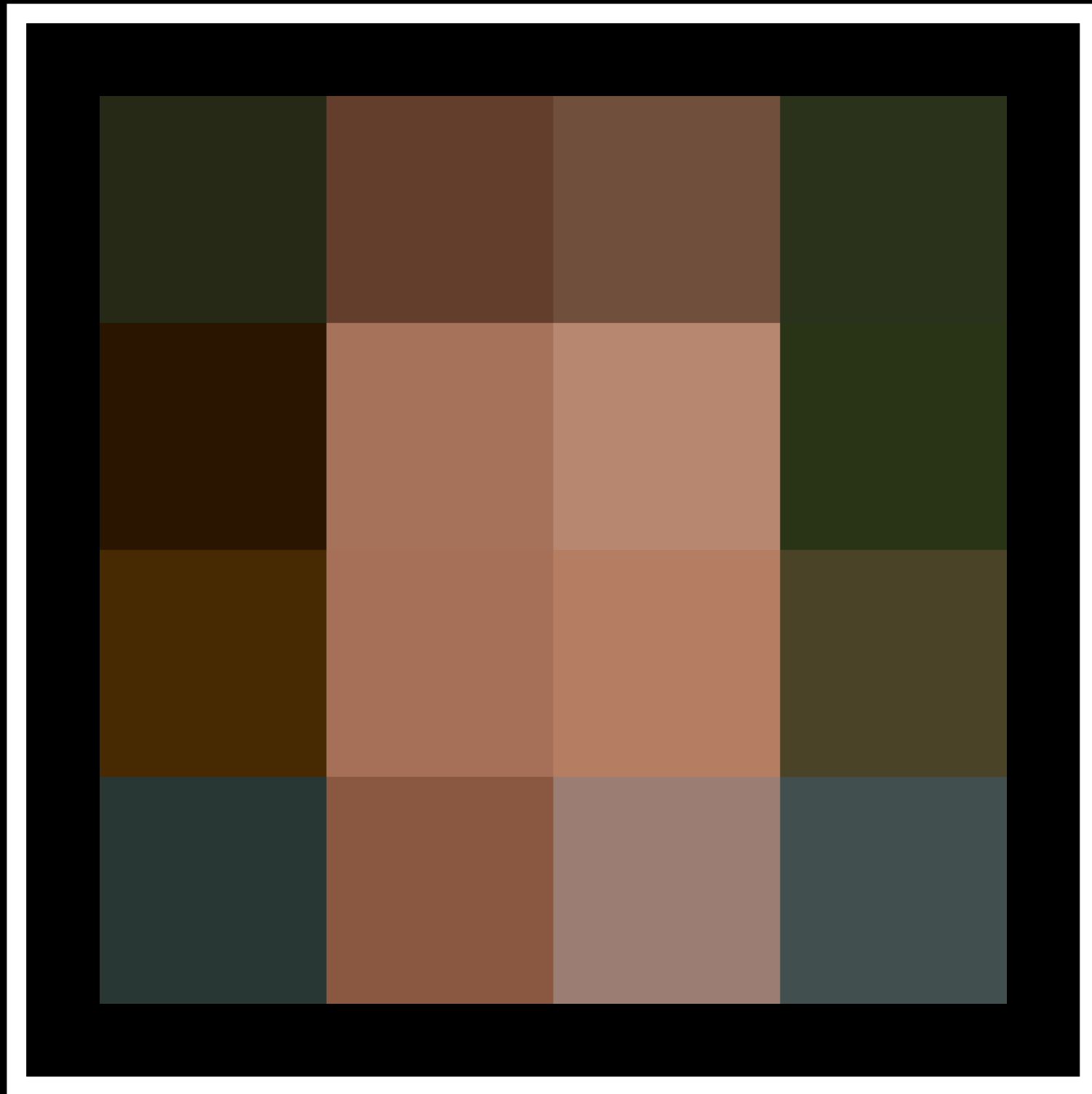












# Artificial Intelligence