

# More Recursion

Tiziana Ligorio

# Today's Plan



Recursion Review

8 Queens Problem

Permutations

Combinations

# Types of Recursion

## Reverse String:

- single recursive call
- Base case: stop => no return value

## Dictionary:

- split problem into halves but solve only 1
- Base case: stop => no return value

## Fractal Tree:

- split problem into halves and solve both
- Base case: stop => no return value

## Factorial:

- single recursive call
- Base case: return a value for computation in each recursive call

# Why/When use recursion

Usually less efficient than iterative counterparts (we will see example later in the course)

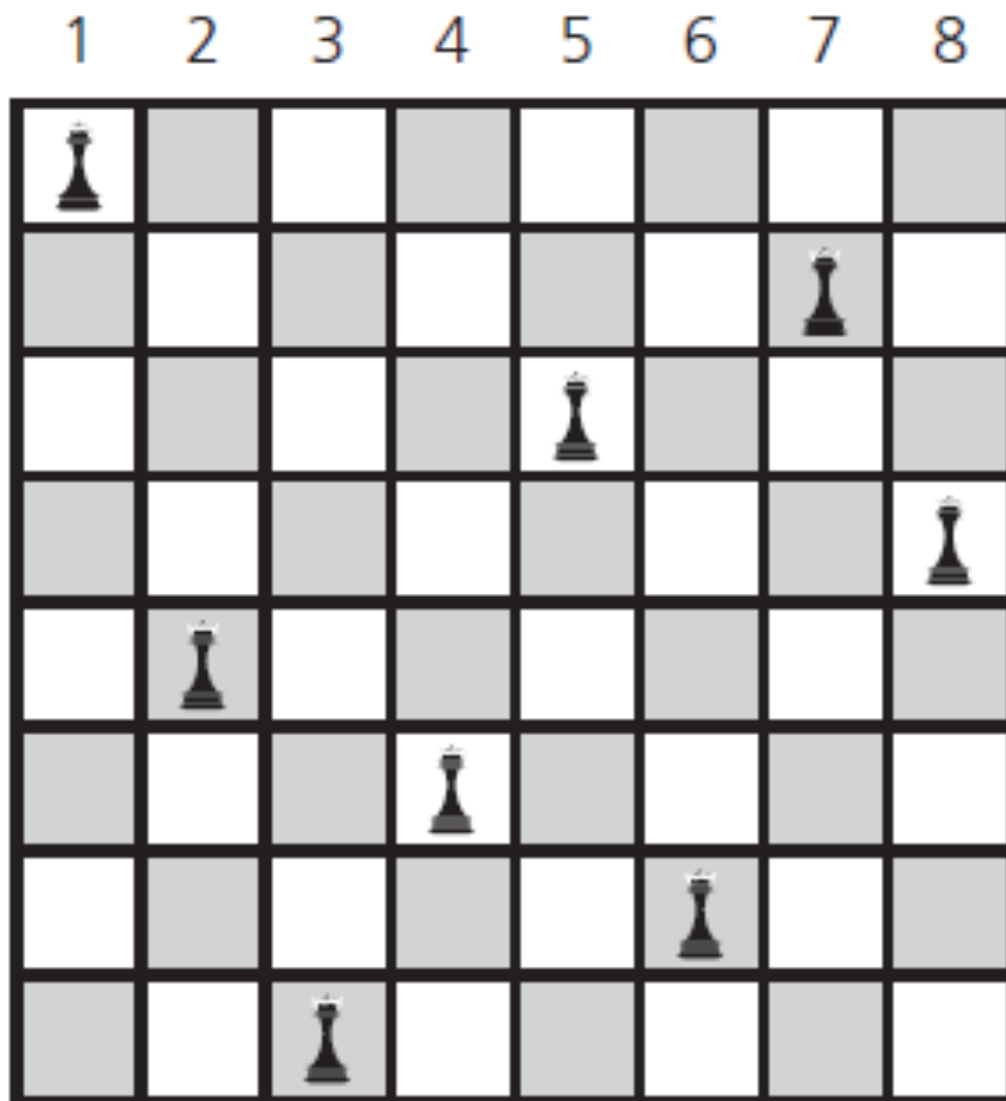
Inherent overhead associated with function calls

Repeated recursive calls with same parameters

Compilers can optimize tail-recursive (recursive call is the last statement in the function) functions to be iterative

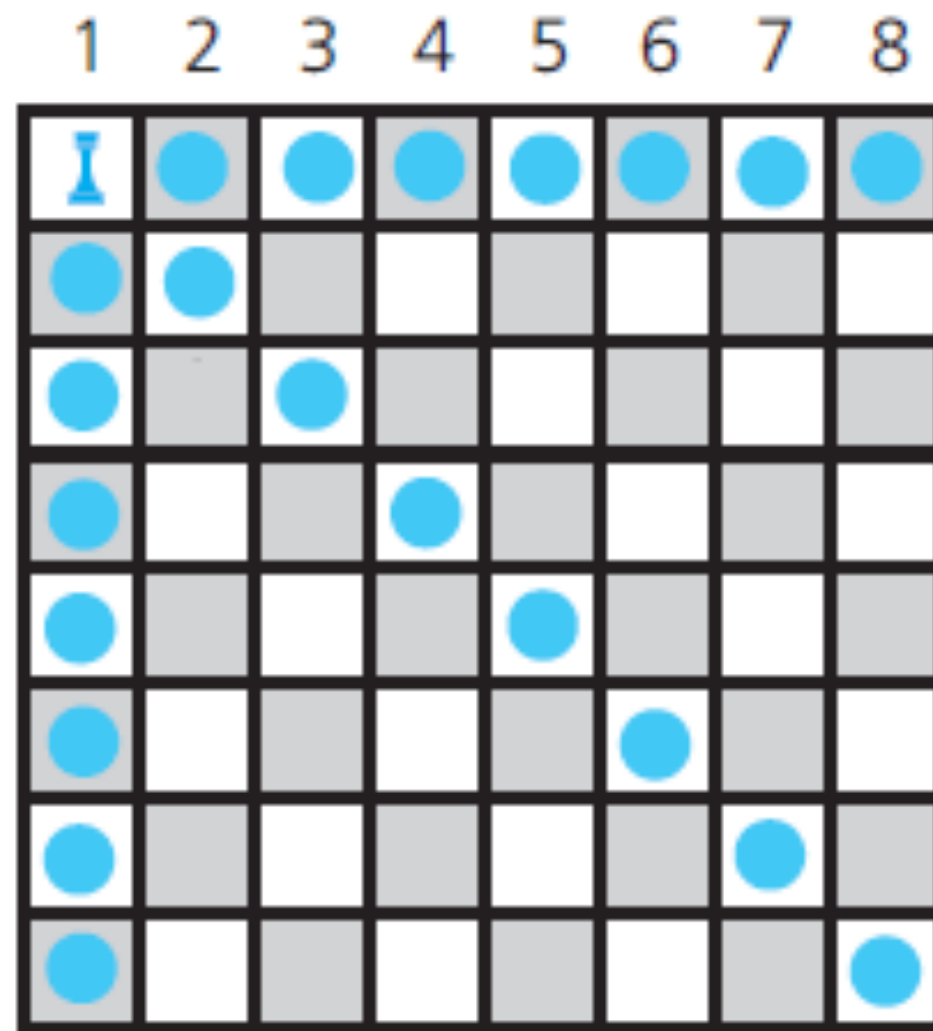
Sometimes logic of iterative solution can be very complex in comparison to recursive solution

# The Eight Queens Problem



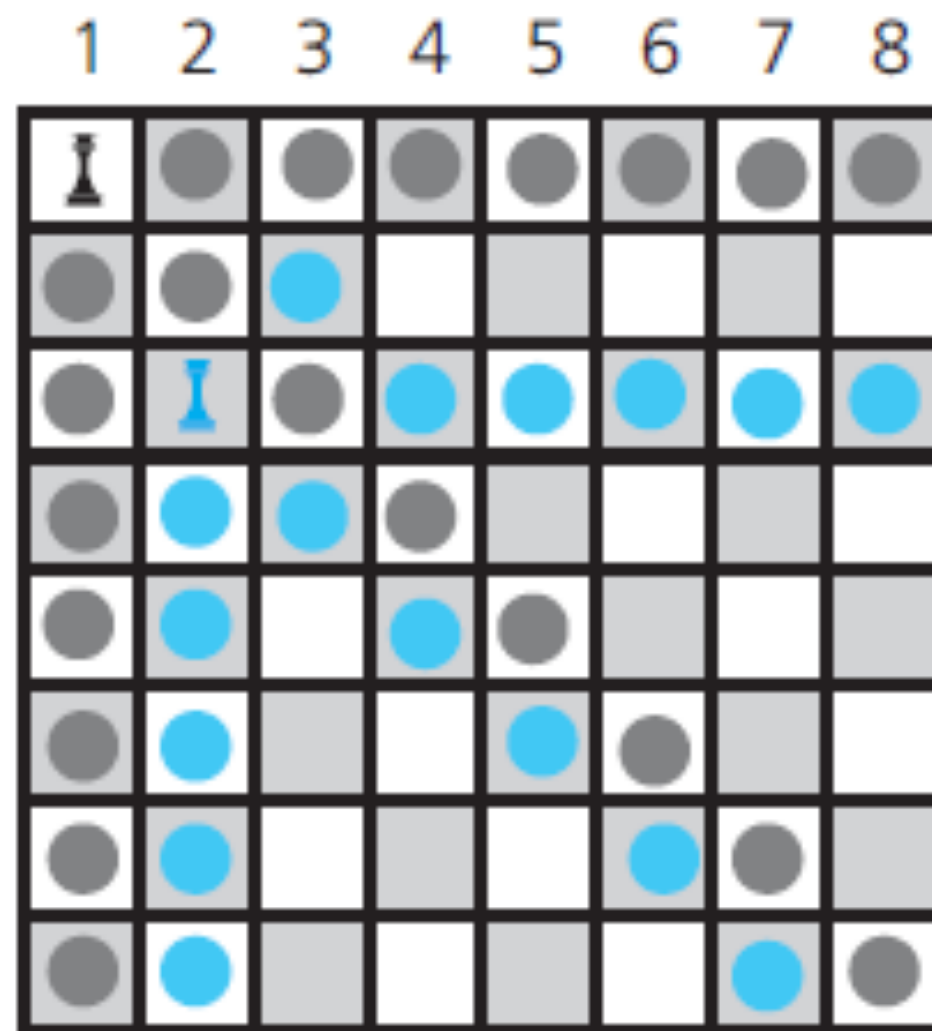
**Place 8 Queens on the board s.t. no queen is on the same row, column or diagonal**

# The Eight Queens Problem



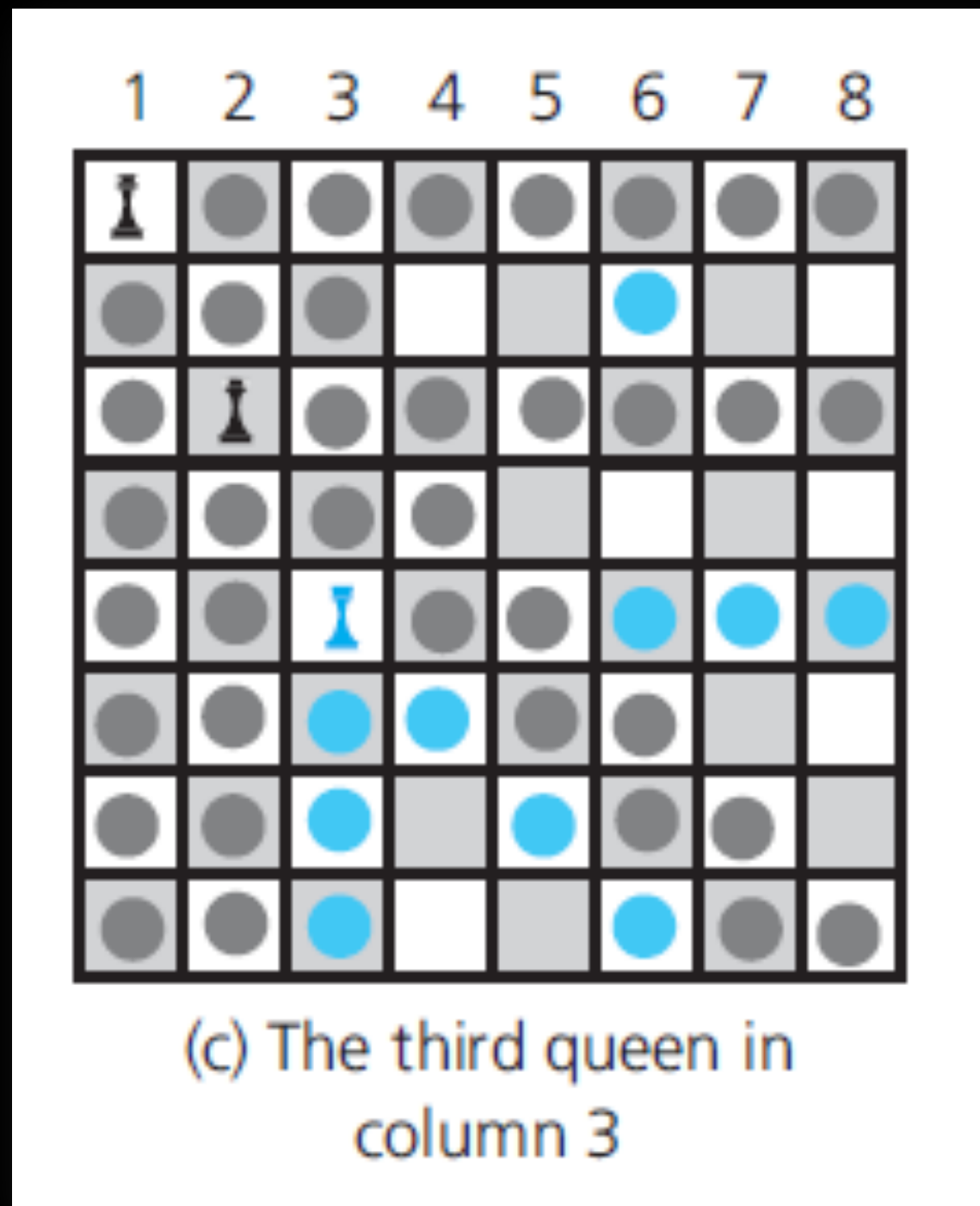
(a) The first queen in column 1

# The Eight Queens Problem



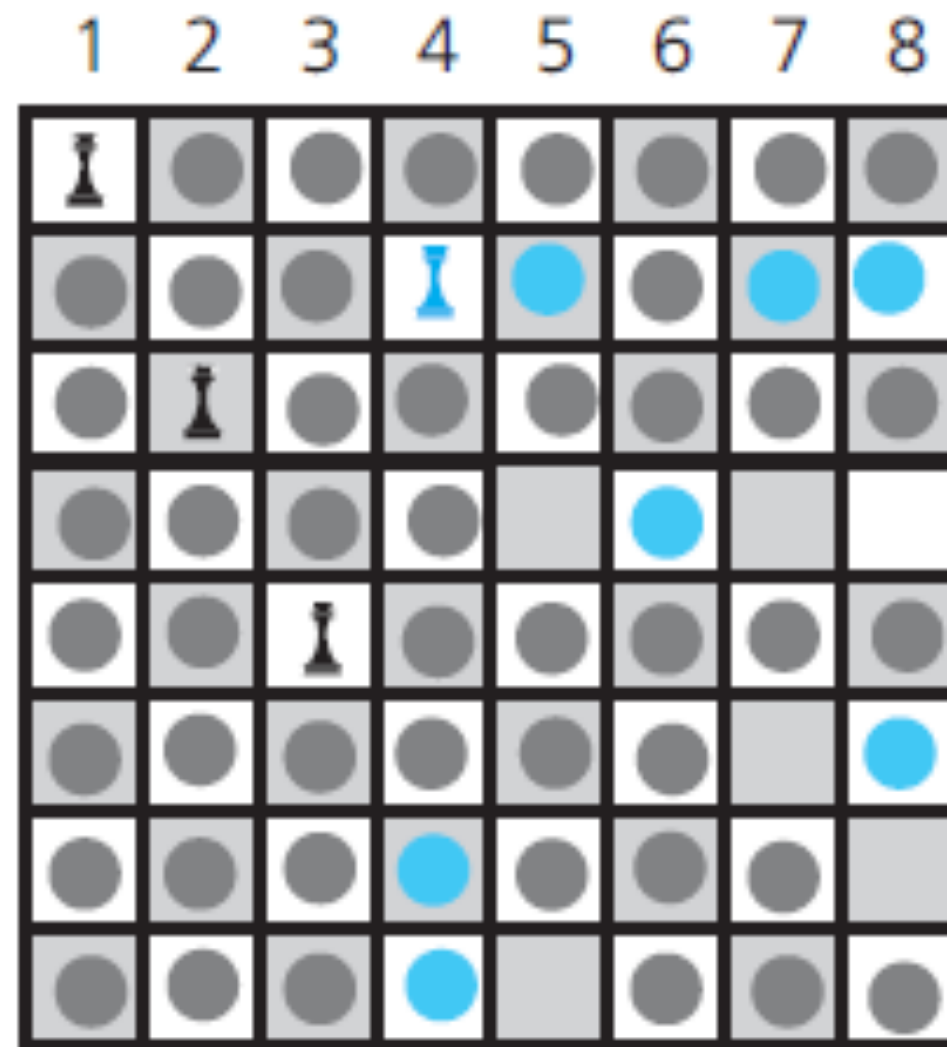
(b) The second queen in column 2

# The Eight Queens Problem



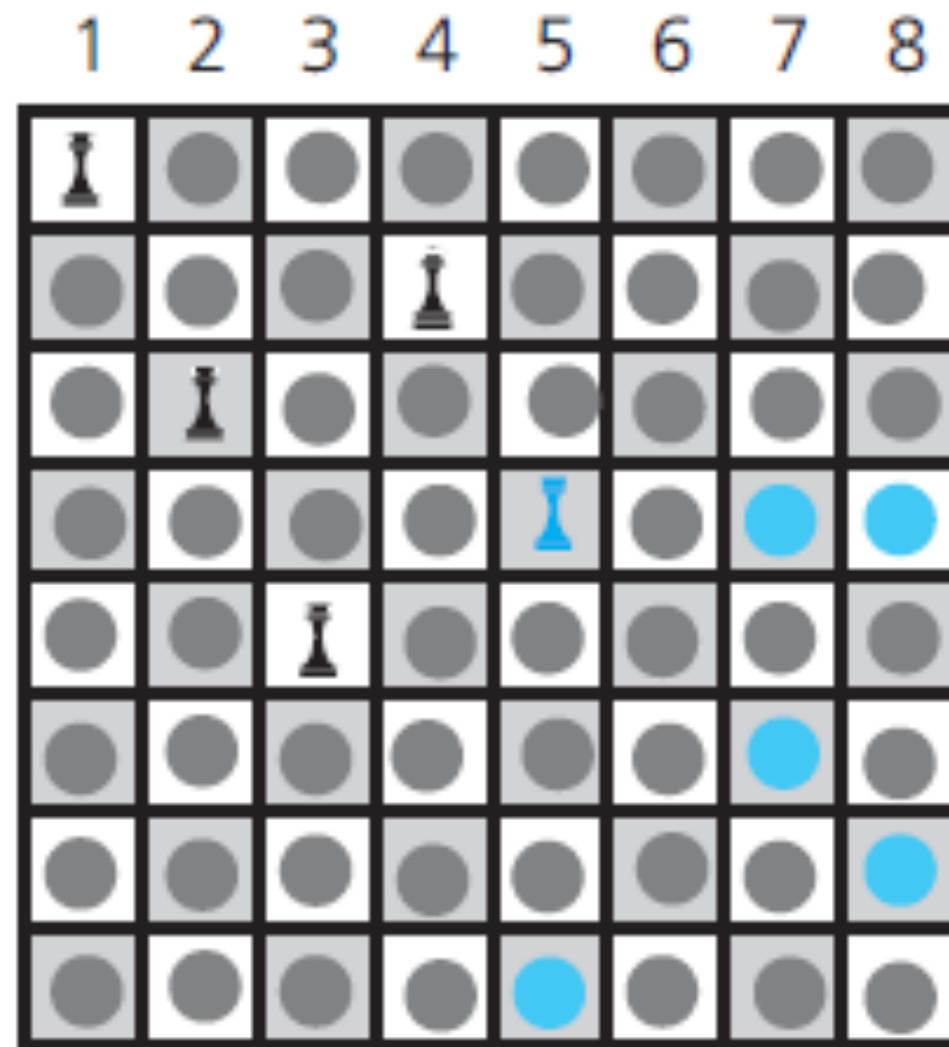


# The Eight Queens Problem



(d) The fourth queen in column 4

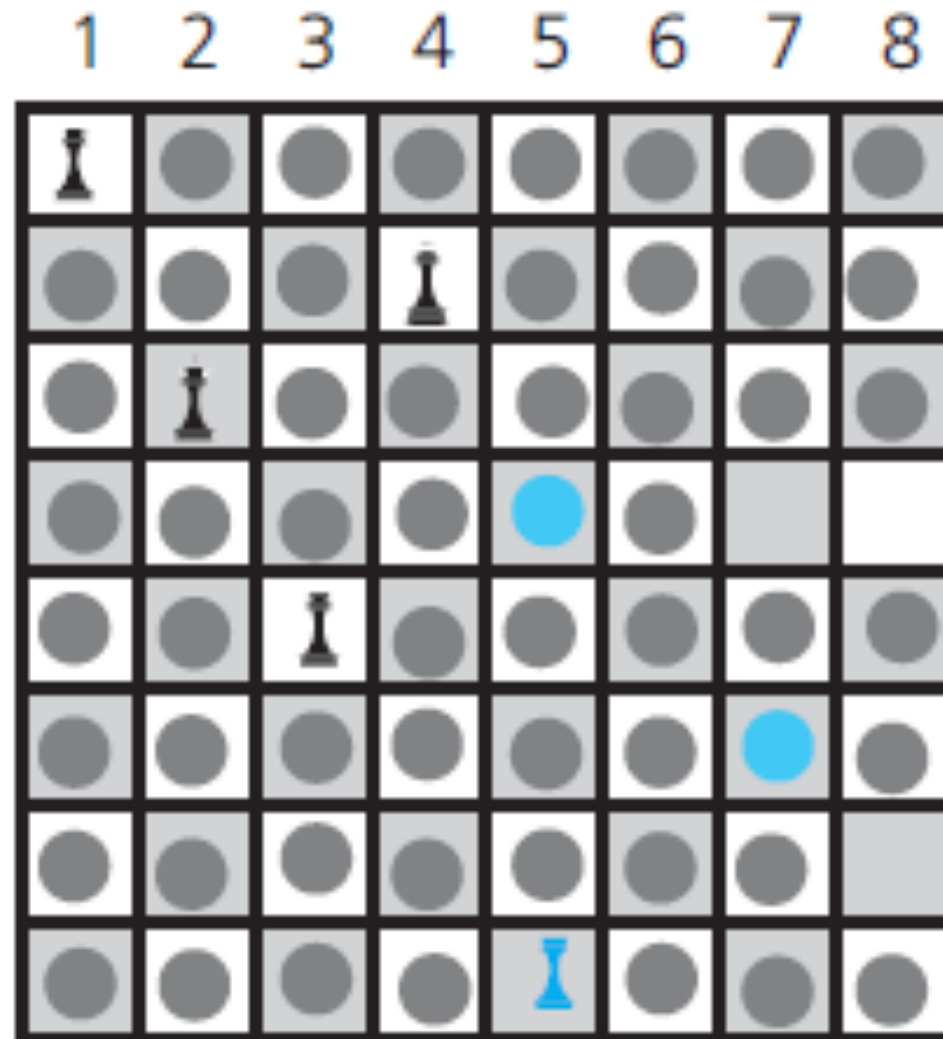
# The Eight Queens Problem



(e) The five queens  
can attack all of column 6

# The Eight Queens Problem

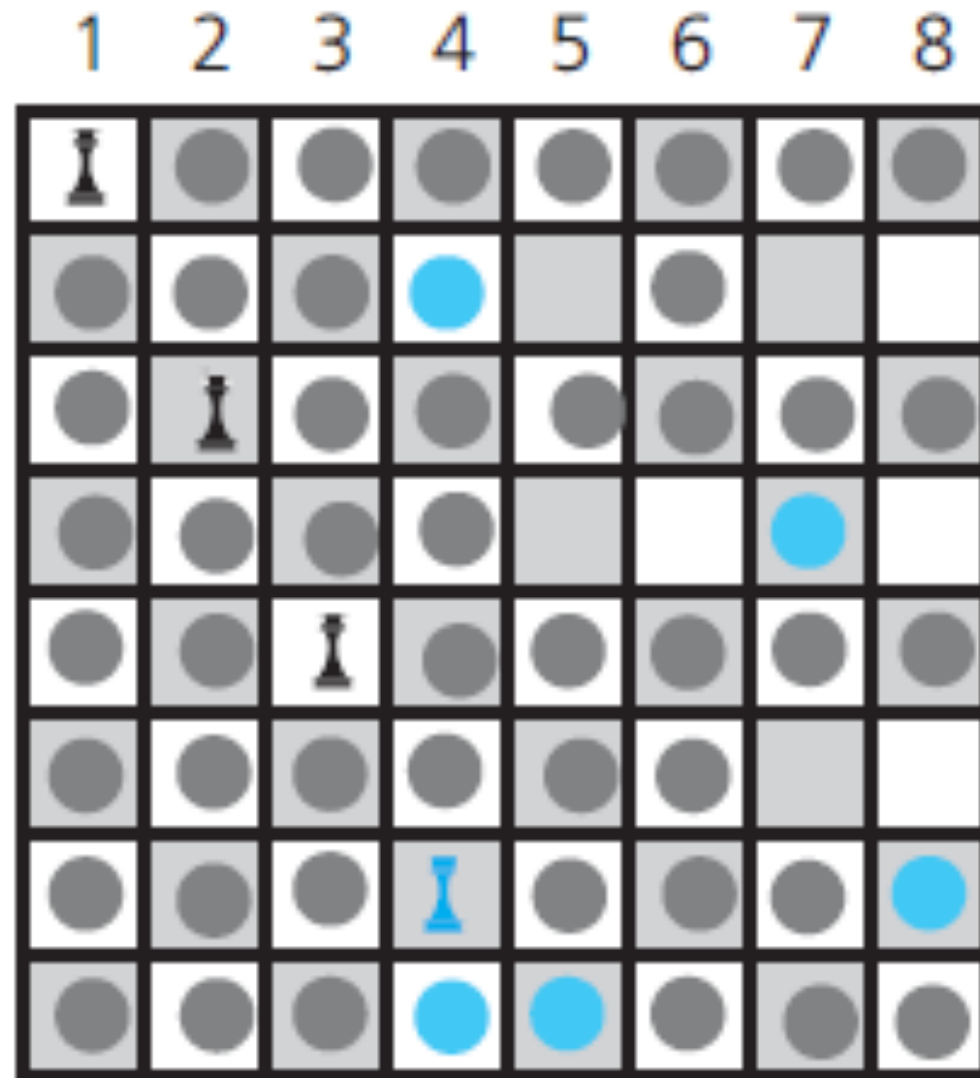
Backtracking!



(f) Backtracking to column 5 to try another square for the queen

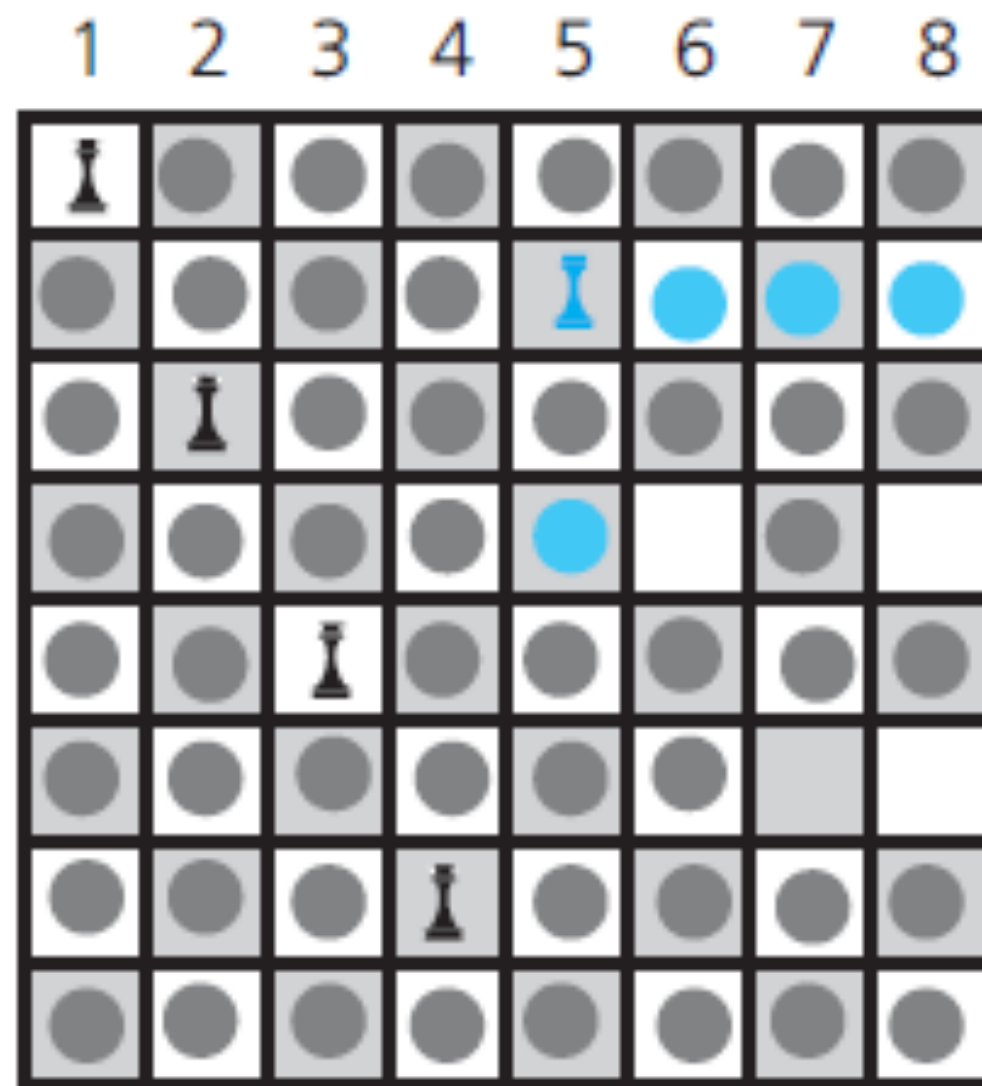
# The Eight Queens Problem

Backtracking!



(g) Backtracking to column 4  
to try another square for  
the queen

# The Eight Queens Problem



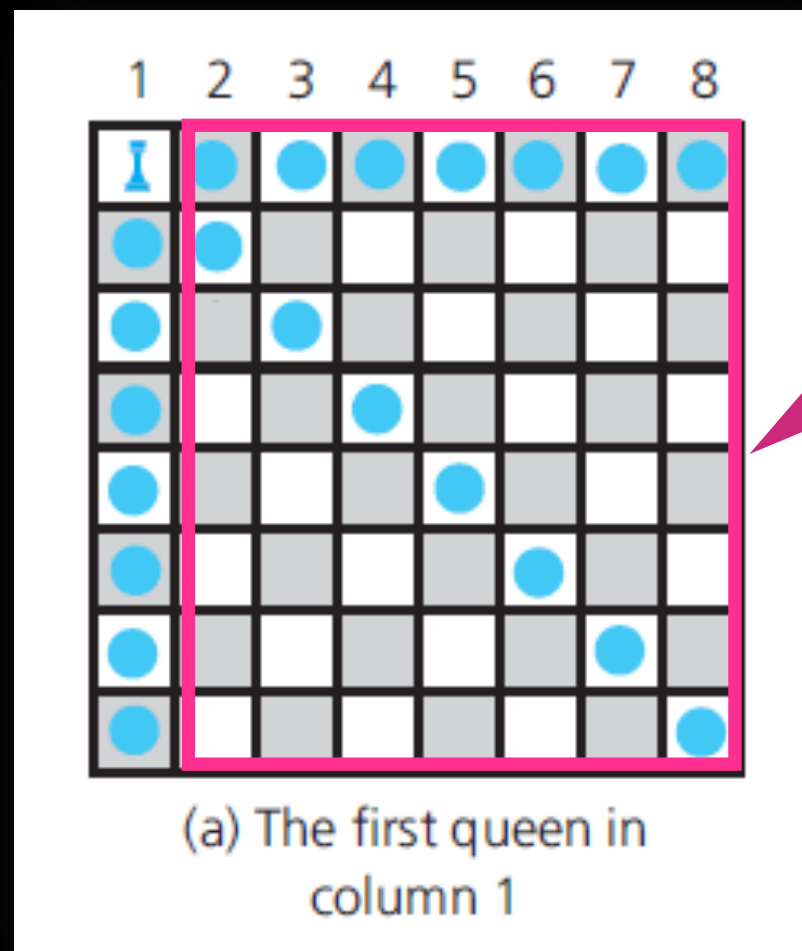
(h) Considering column  
5 again

# The Eight Queens Problem

How can we express this problem recursively?

# The Eight Queens Problem

How can we express this problem recursively?



Place queen on column  $i$   
Recursively solve on  
columns  $(i+1)$  to 8

# The Eight Queens Problem

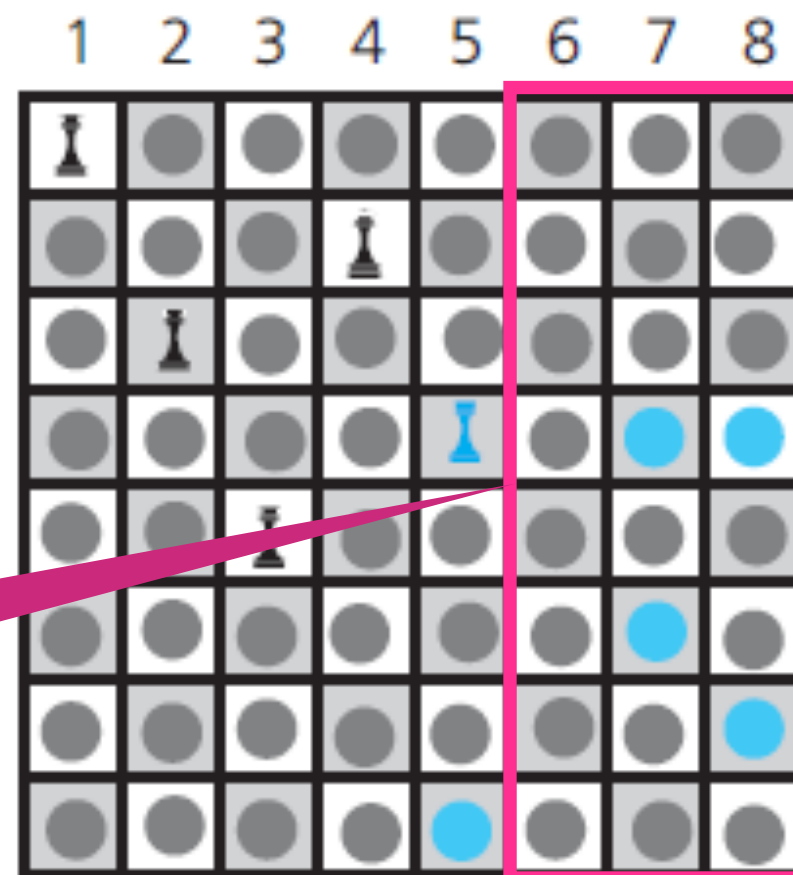
How do we backtrack?



# The Eight Queens Problem

How do we backtrack?

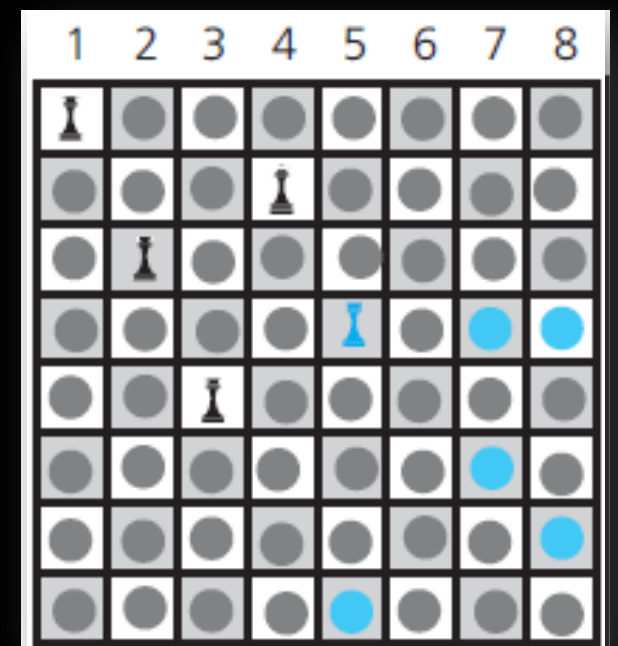
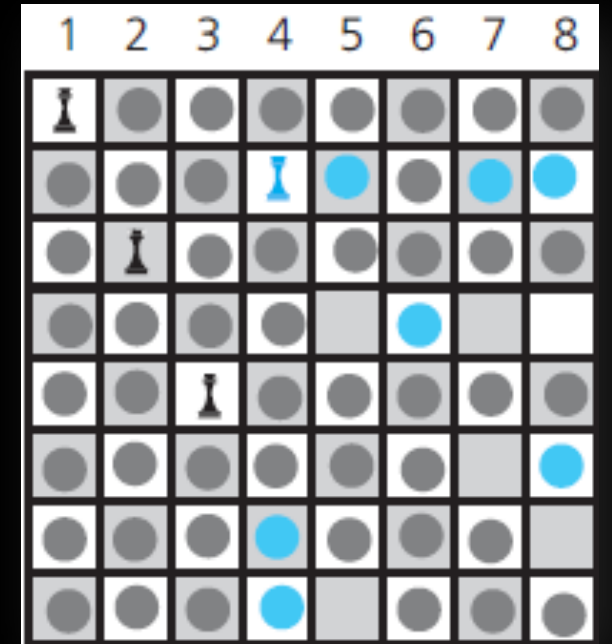
Communicate to calling function that there are no options left, it should try something else!



(e) The five queens can attack all of column 6

# The Eight Queens Problem

```
bool placeQueens(board, column)
{
    if(column > BOARD_SIZE)
        return true; //Problem is solved!
    else
    {
        while(there are safe squares in this column)
        {
            place queen in next safe square;
            → if(placeQueen(board, column+1)) //recursively look forward
                return true; //queen safely placed
        }
        return false; //recursive backtracking
    }
}
```

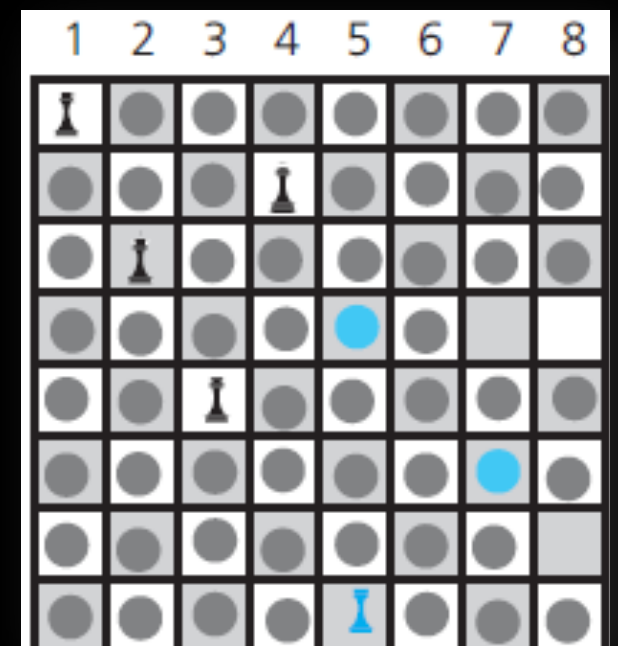
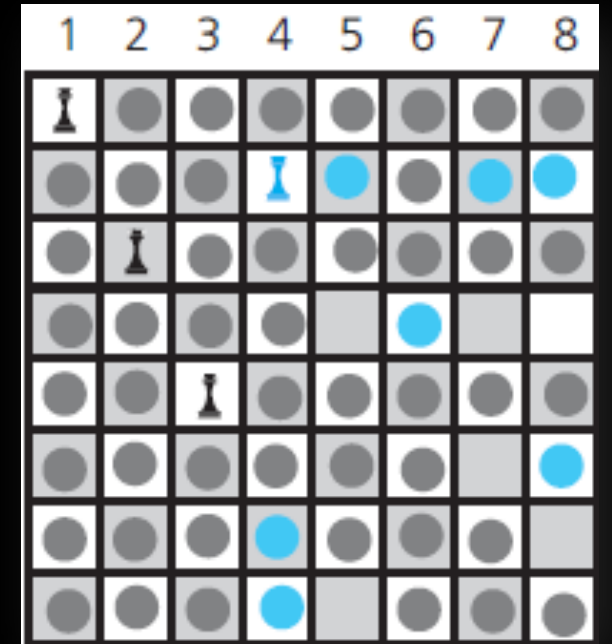


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        }
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    }
}

```



# Think Algorithmically

*“Experienced Computer Scientists analyze and solve computational problems at a level of **abstraction** that is beyond that of any particular programming language / representation / implementation”*

## Algorithm Design

- Identify the problem (input, output, states)
- Come up with a procedure that will lead to solution
- Independent of implementation detail



**Initial phase/step**

## **Model** your problem/data

- **represent** the problem to support your algorithm

## **Implement** solution

- Language
- Data structure
- Implementation detail

# Think Algorithmically

- Takes practice
- The more you see/do the easier it gets
- There are some frameworks that can guide you, we have seen only a few, you will continue to learn more throughout your career

E.g.

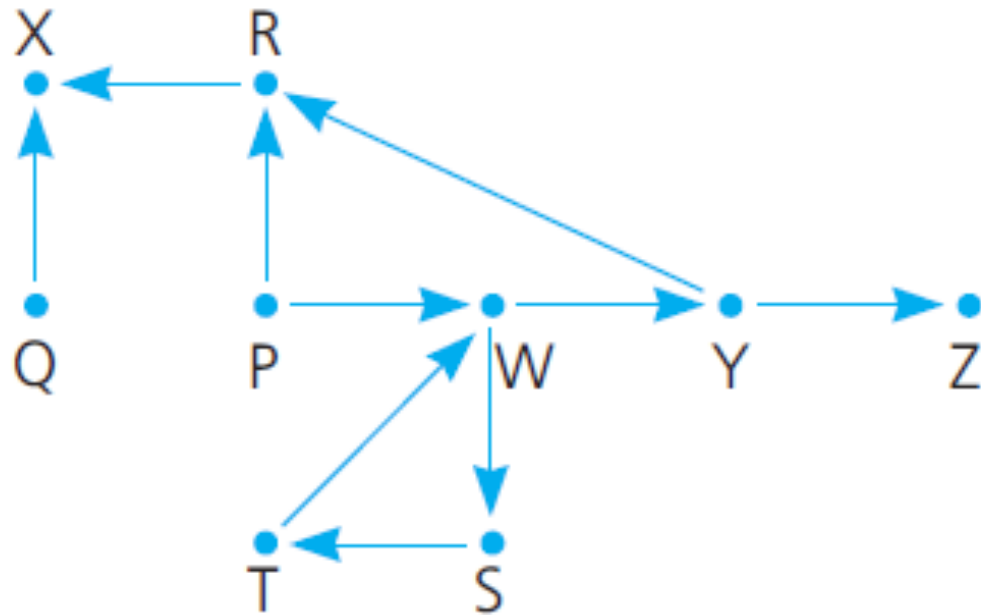
- Can I cast this as a backtracking problem?
- Can I cast this as a decision-making / decision tree problem?
- Do I need to enumerate all solutions?
- Am I looking for best/optimal solution?

# Lecture Activity

Write **PSEUDOCODE** for a **RECURSIVE** function that finds a path from origin to destination.  
Assume cities are visited in alphabetical order.

```
bool findPath(map, origin, destination)
```

**Origin = P** , **Destination = Z**



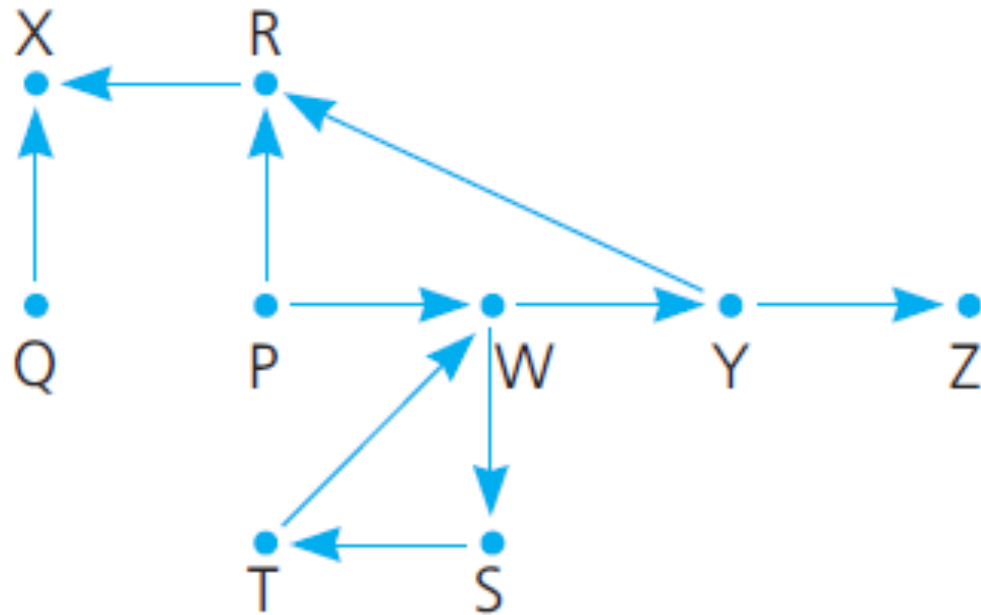
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**P**

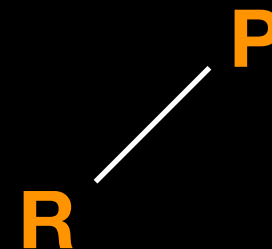
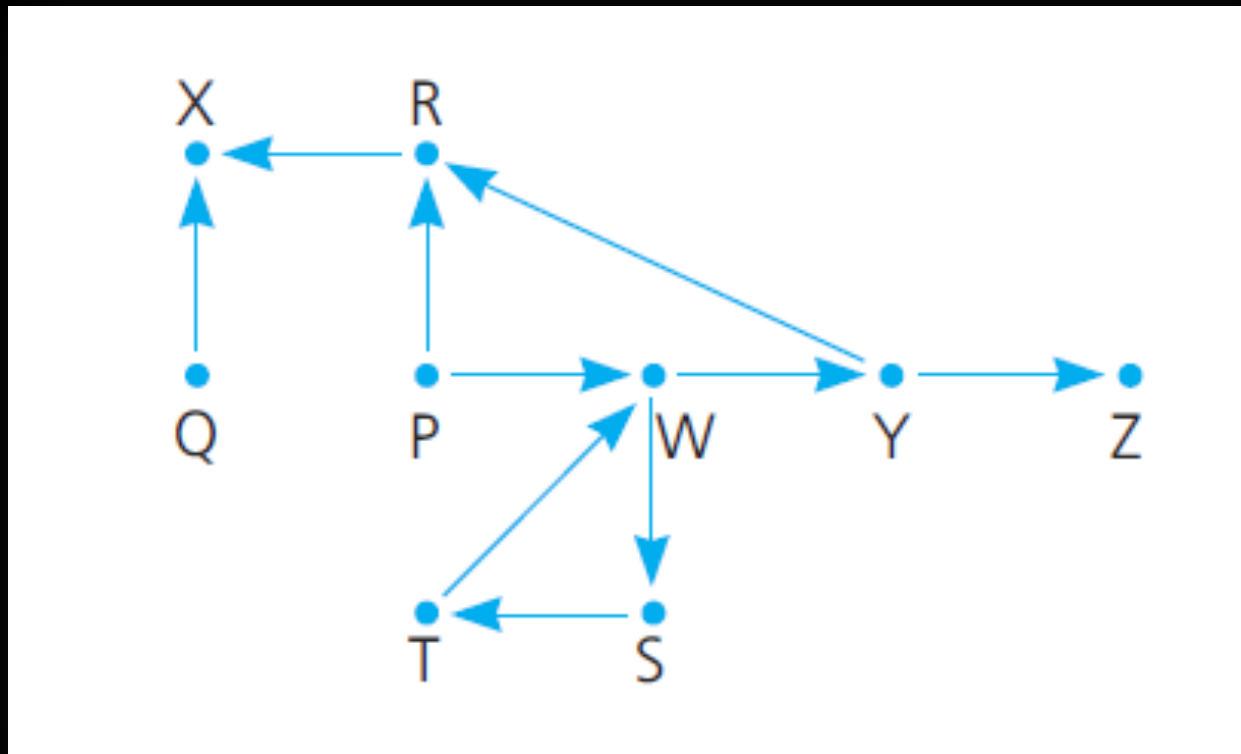


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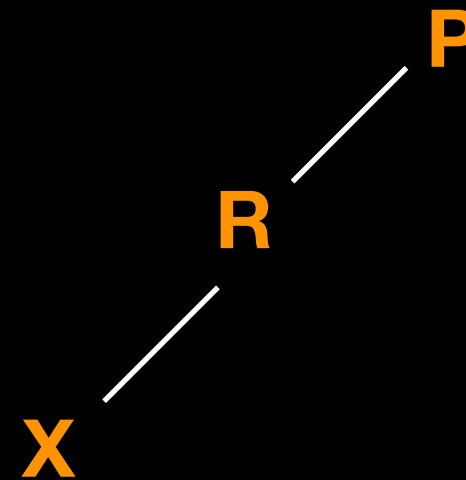
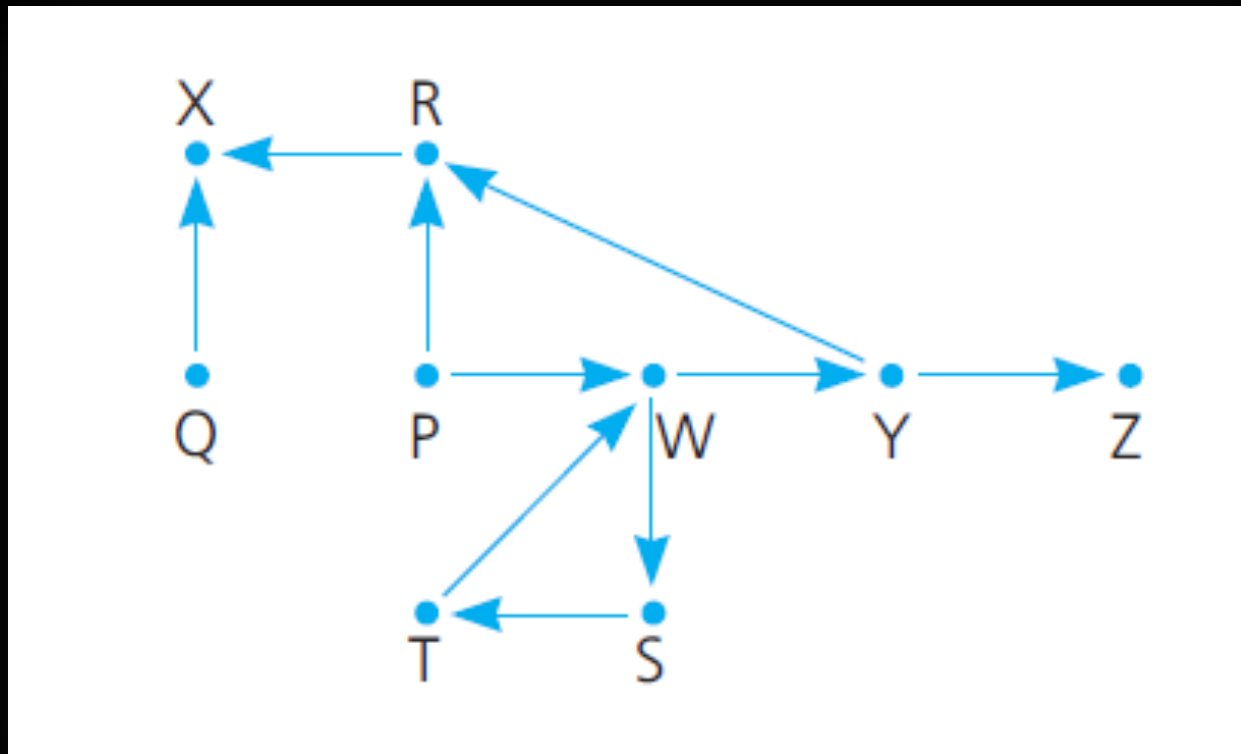


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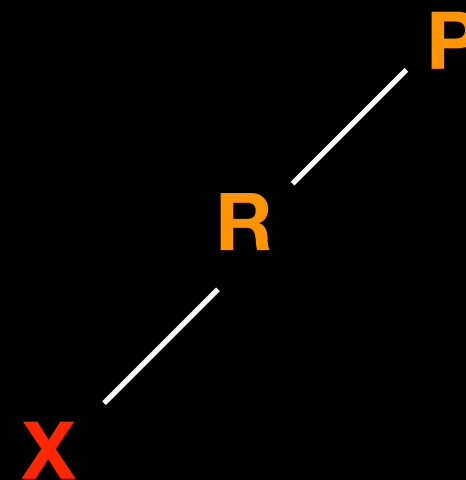
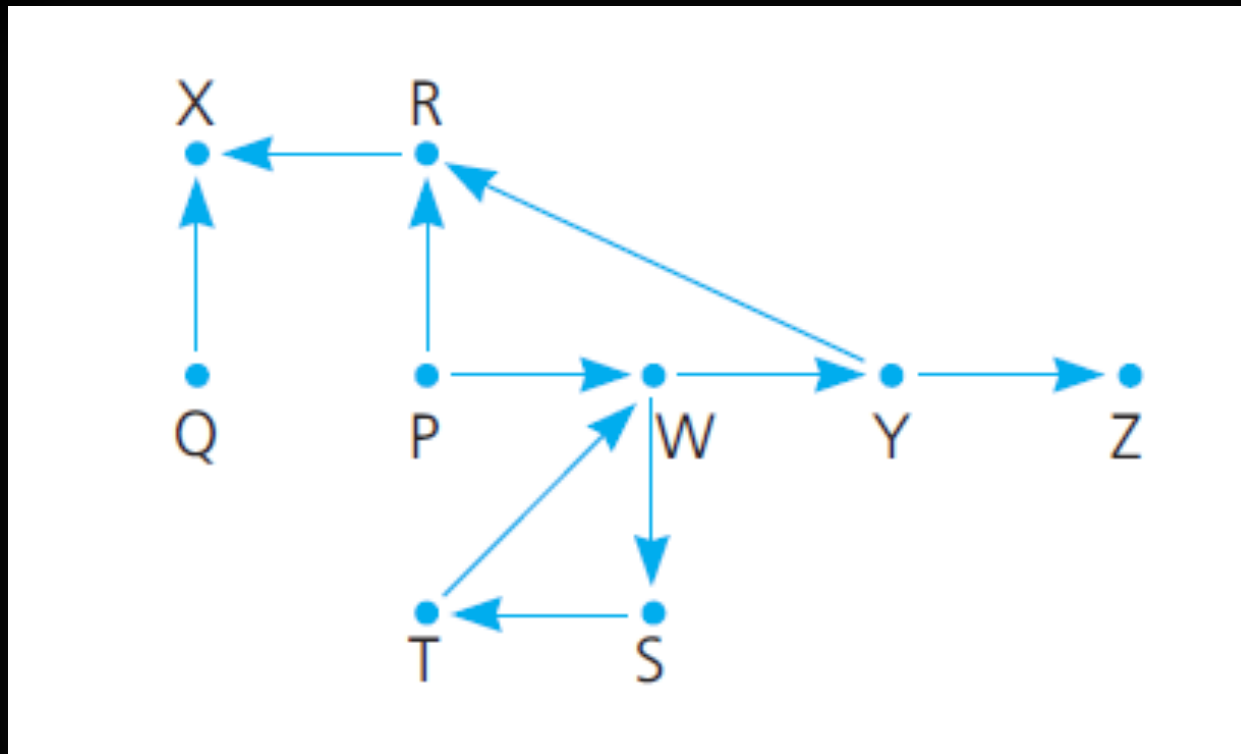


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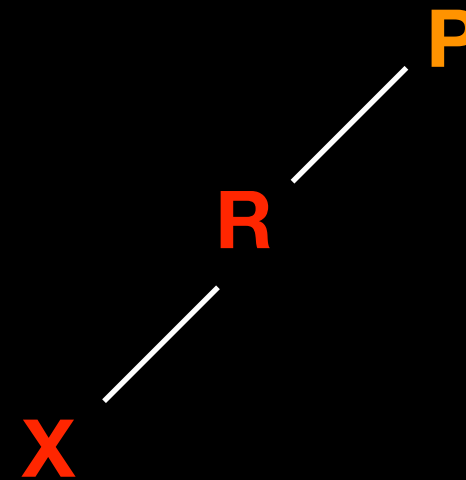
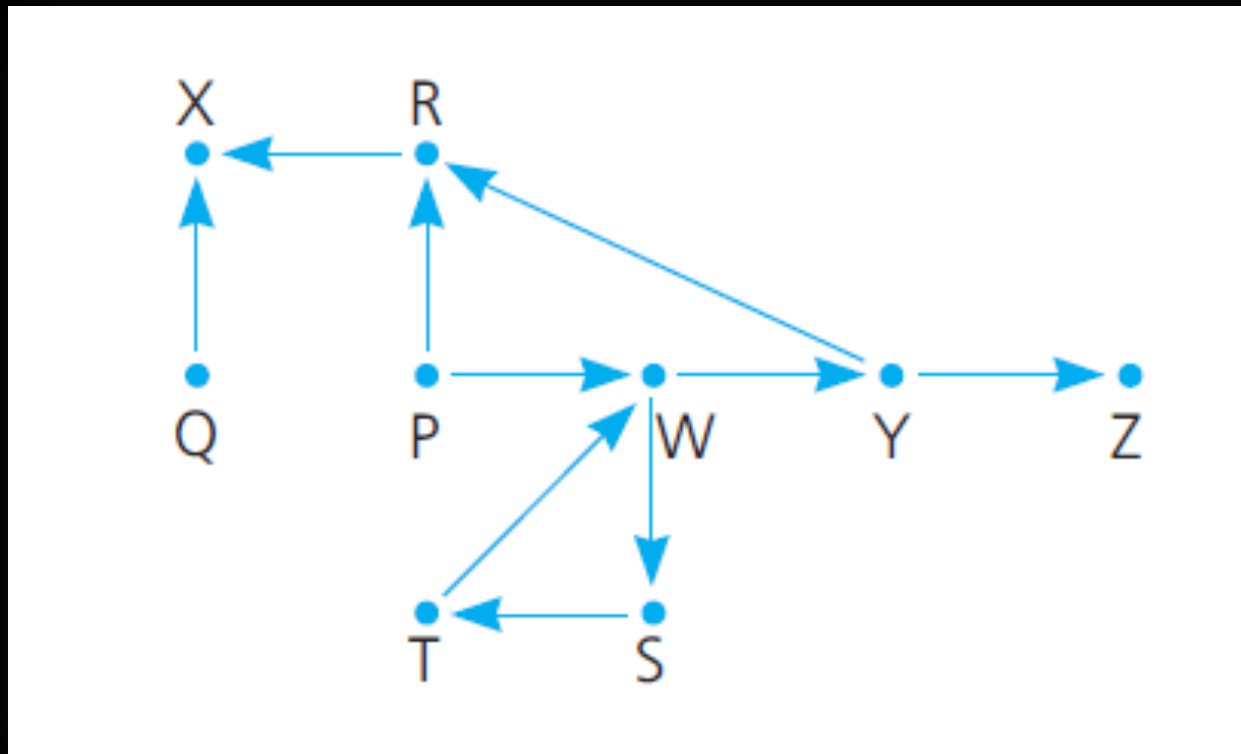


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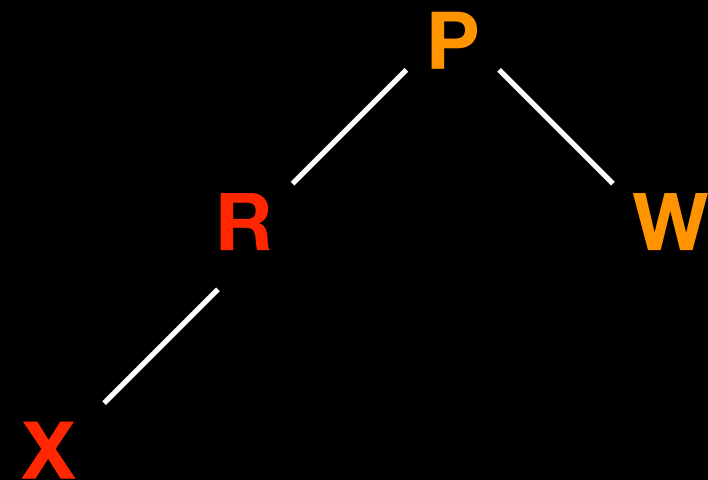
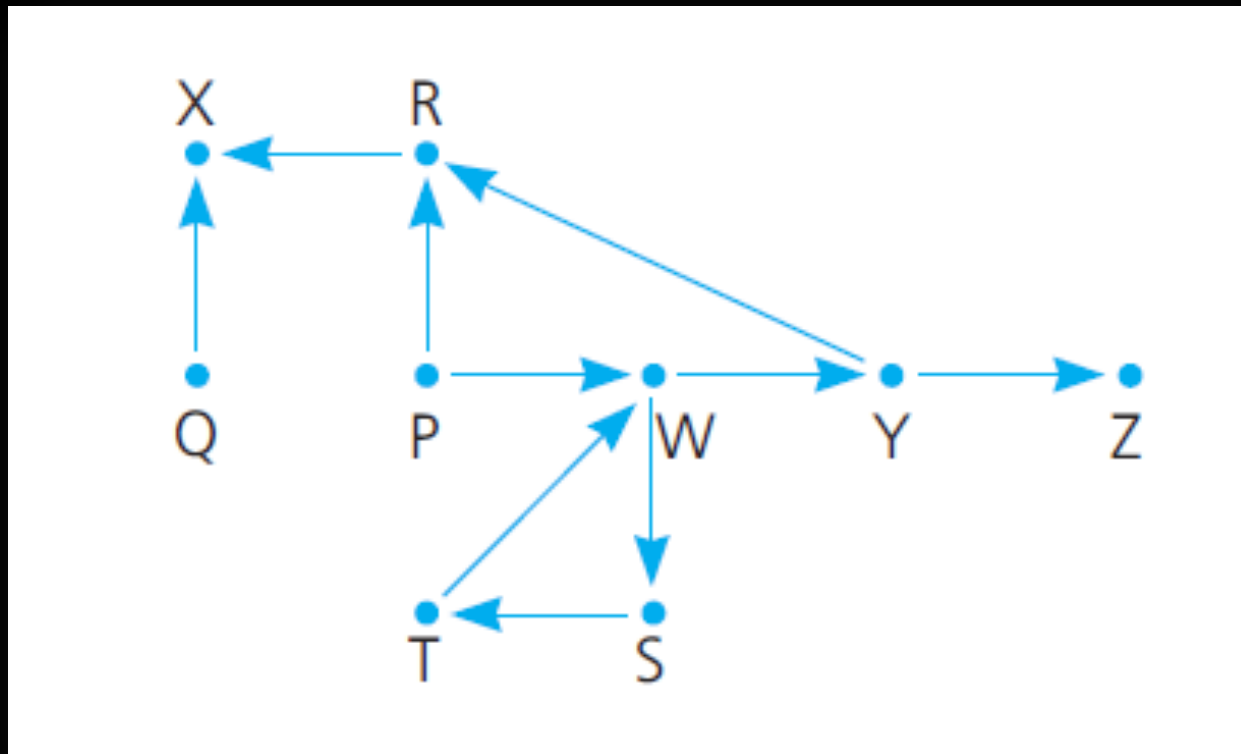


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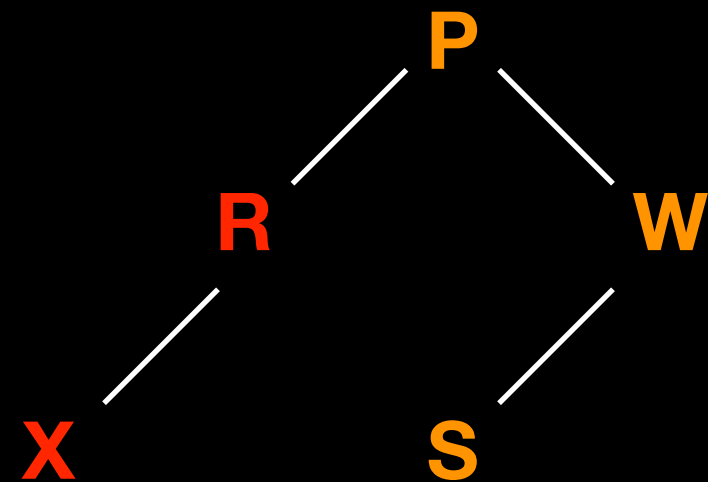
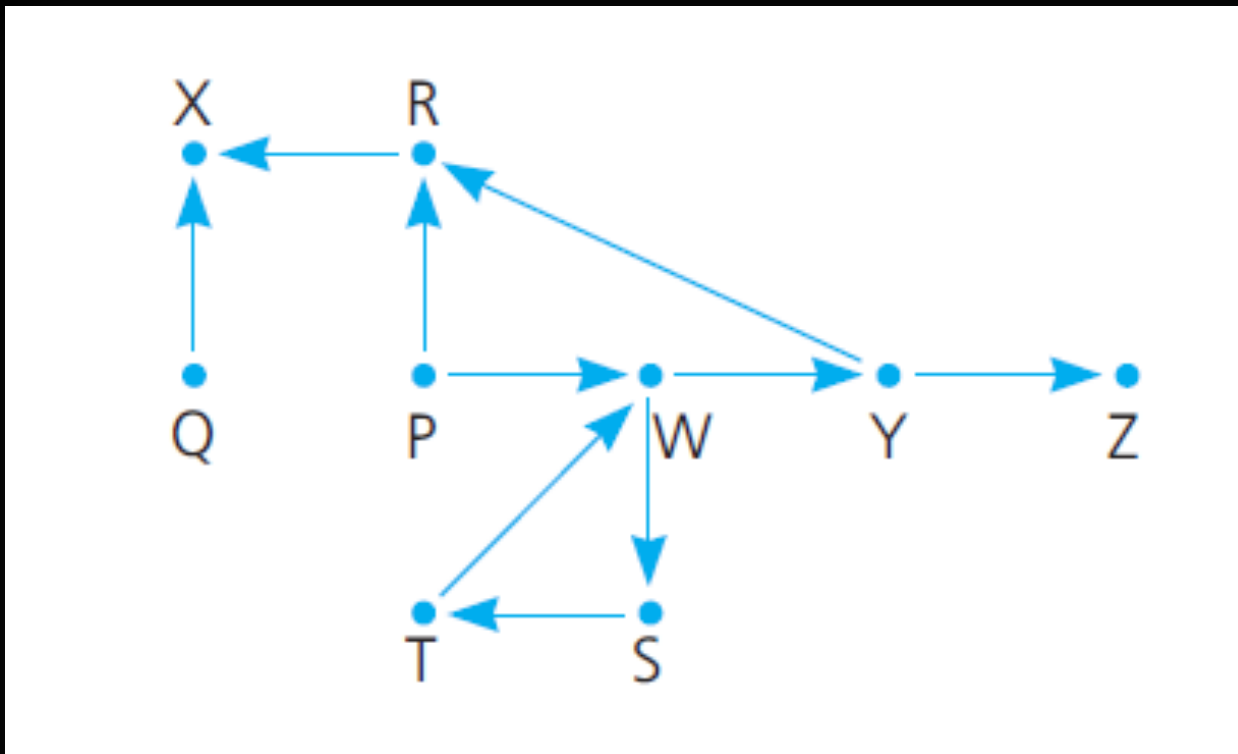


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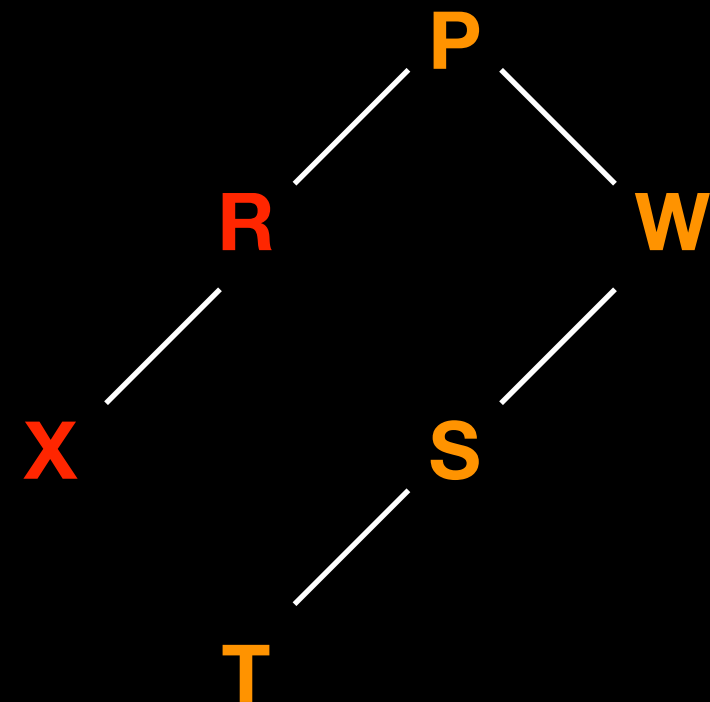
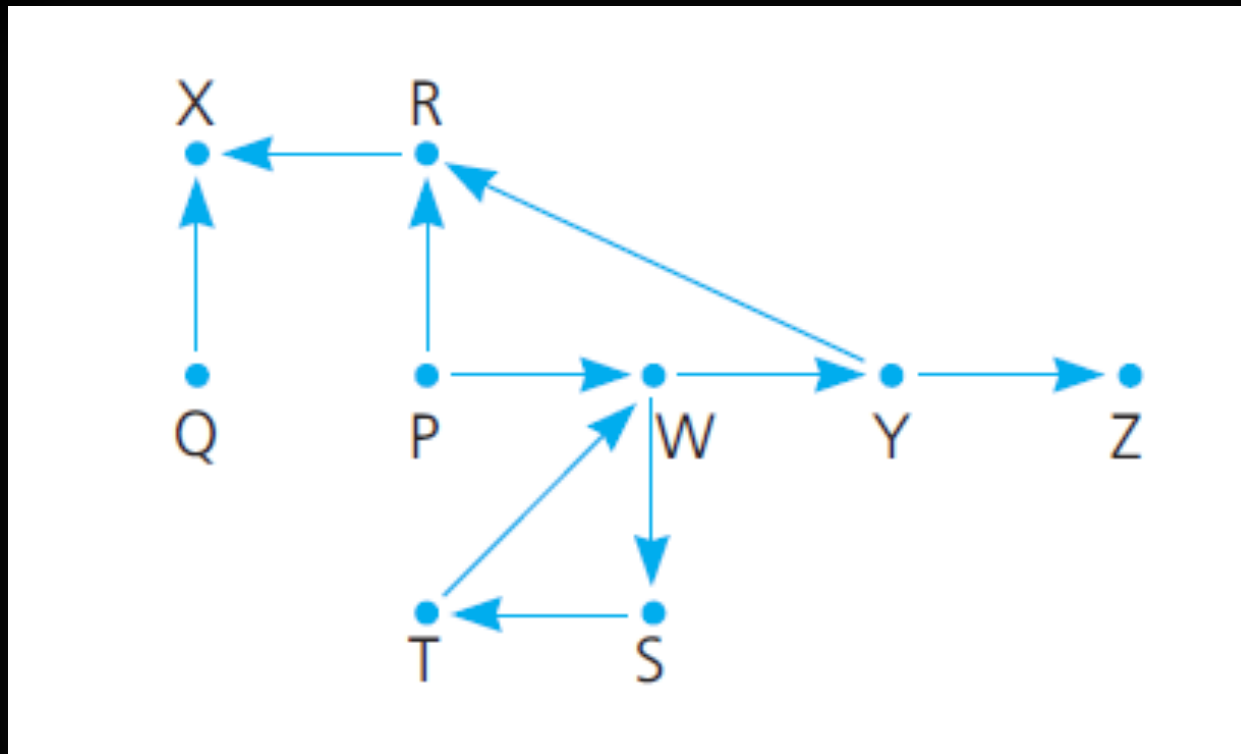


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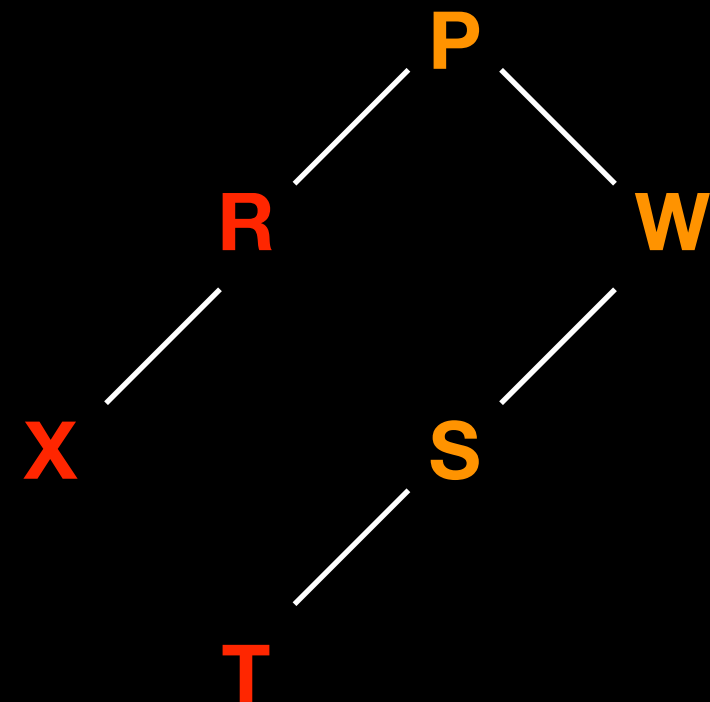
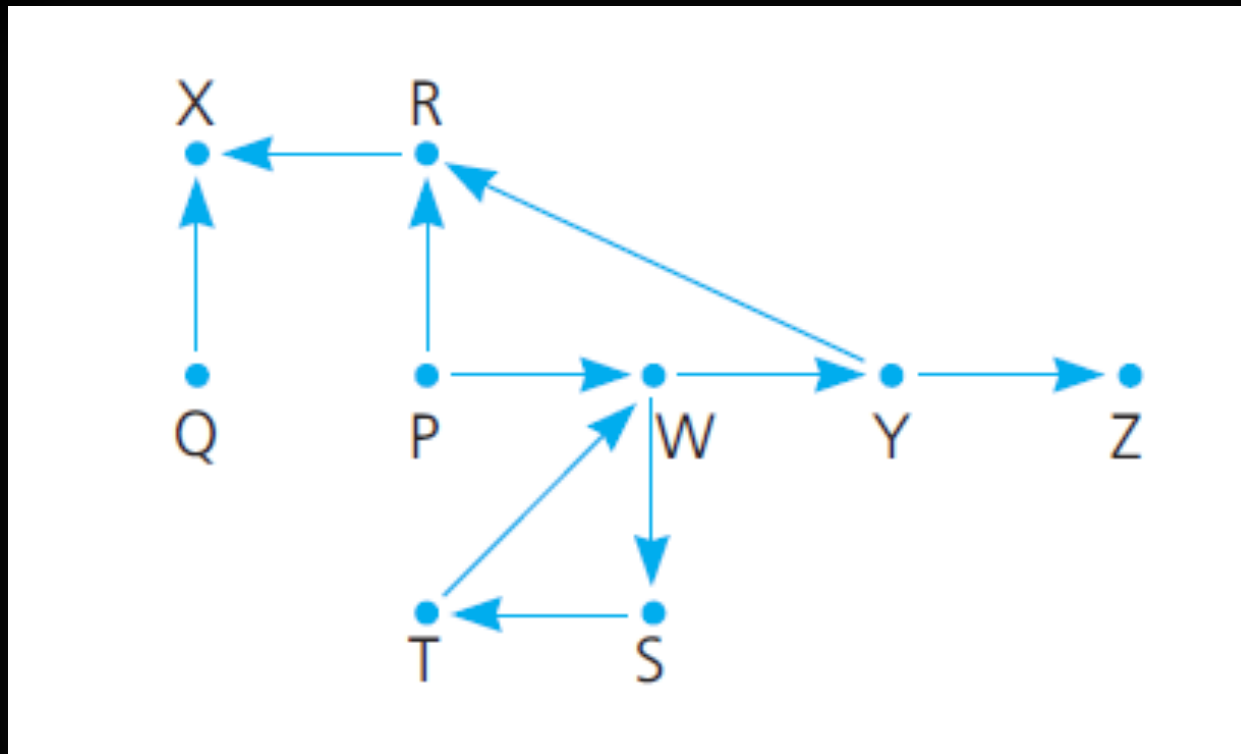


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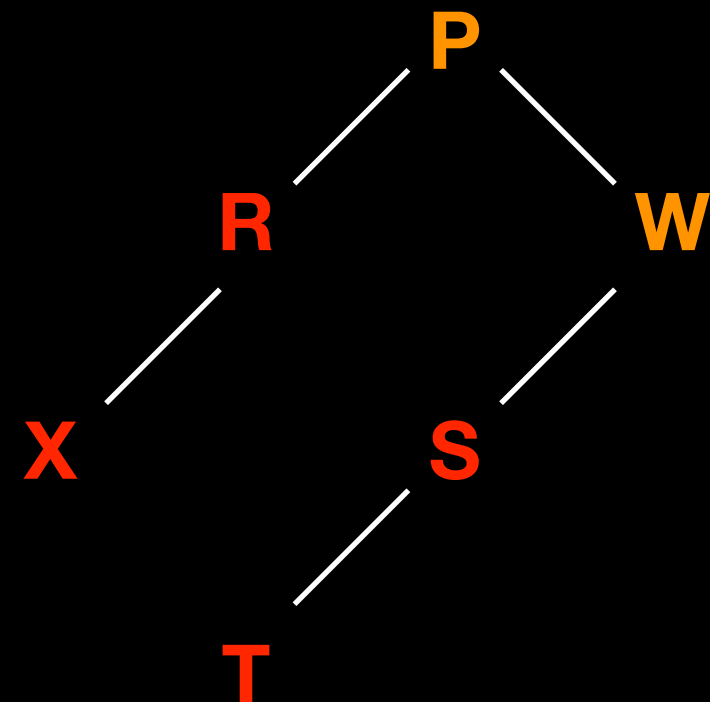
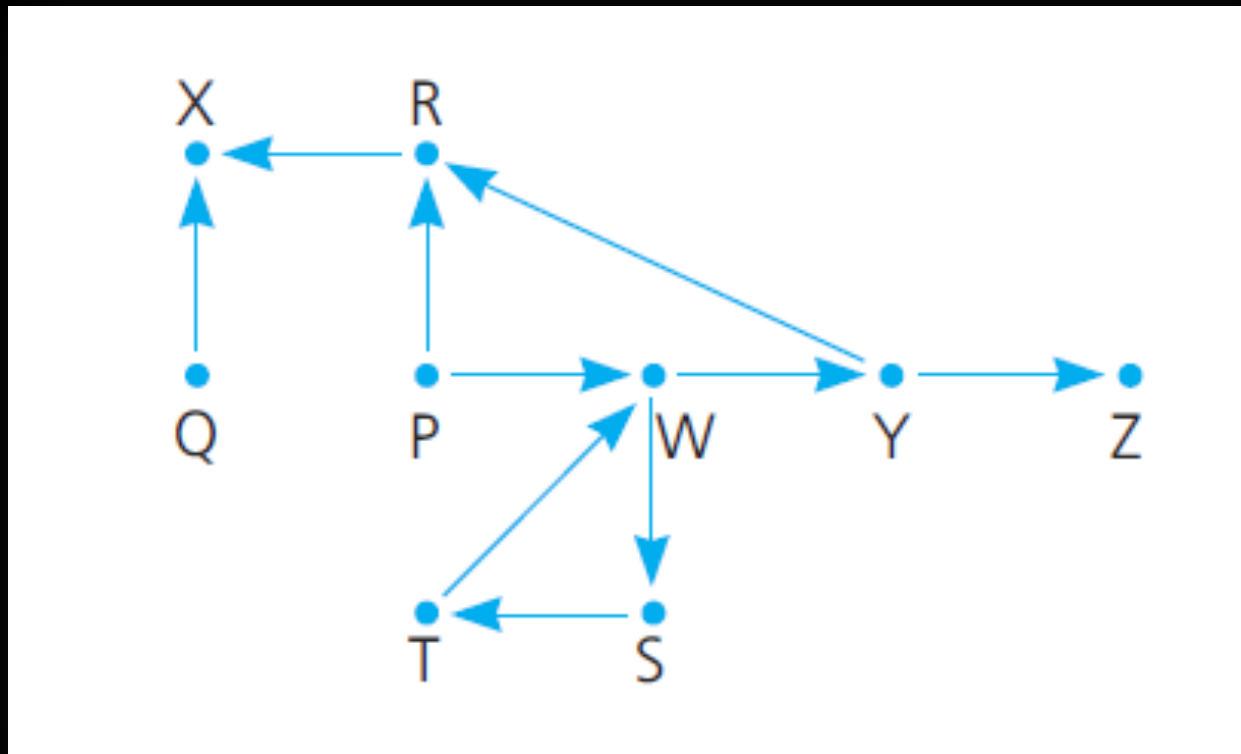


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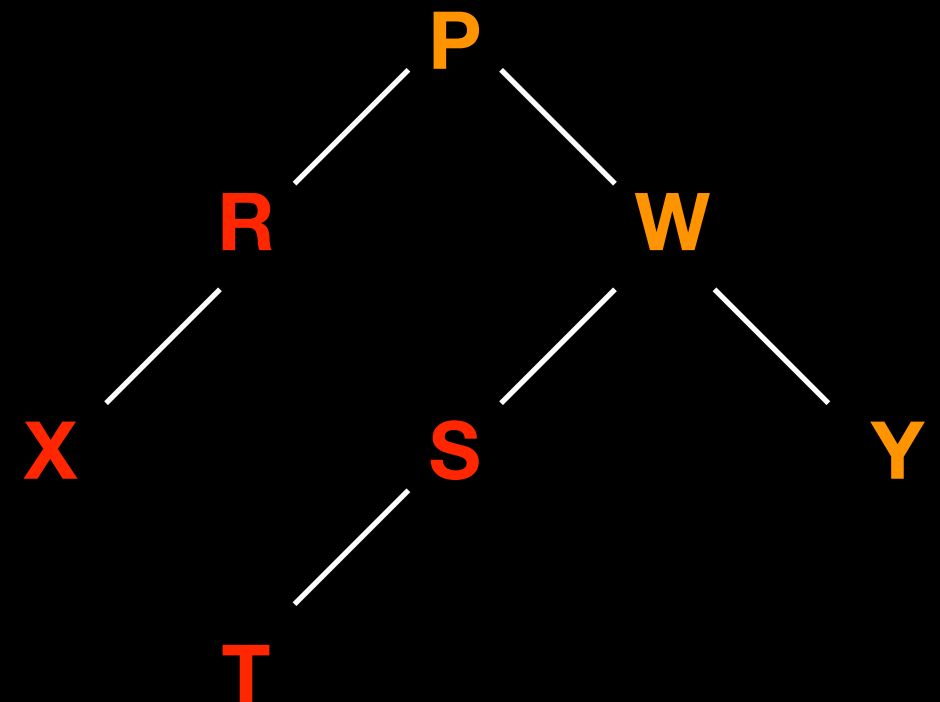
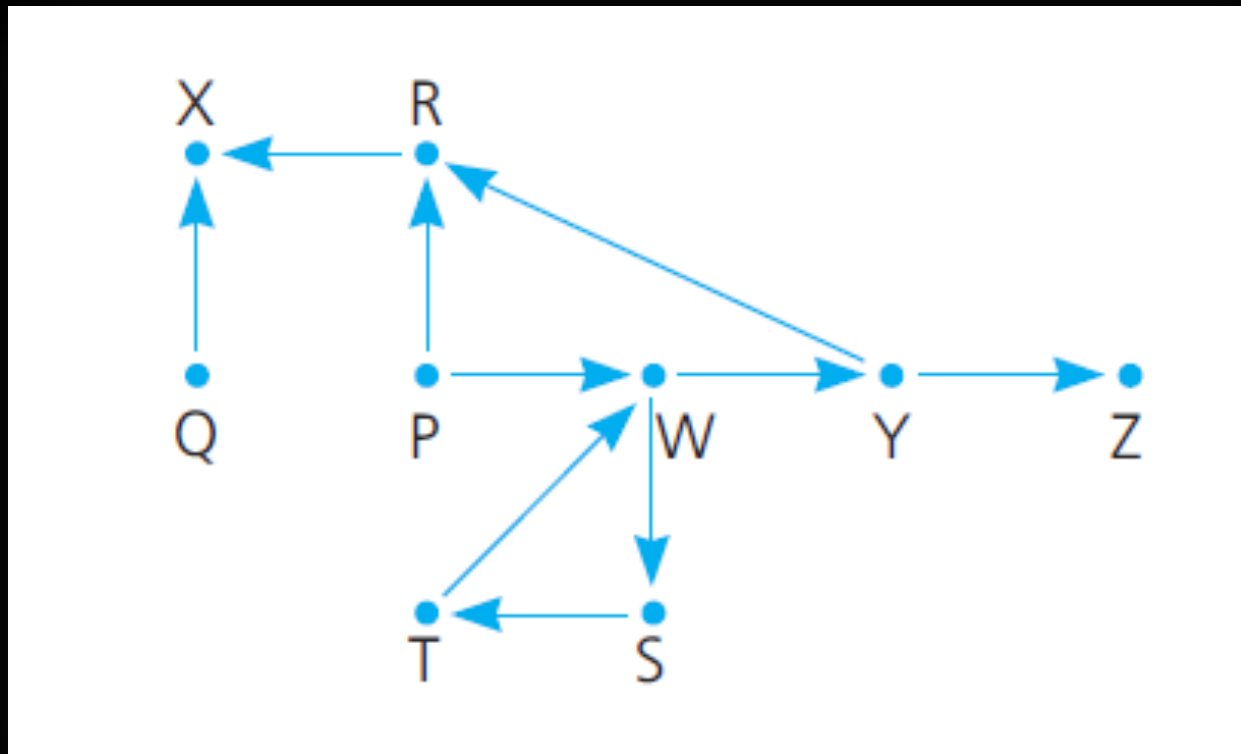


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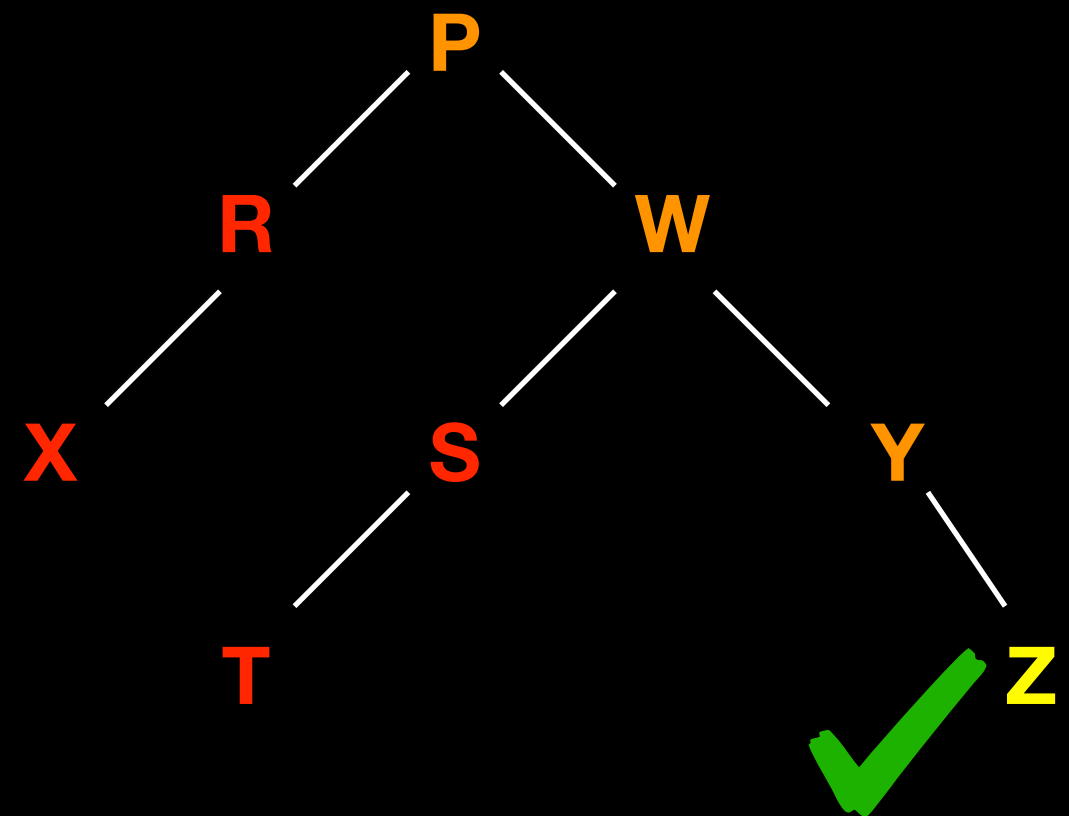
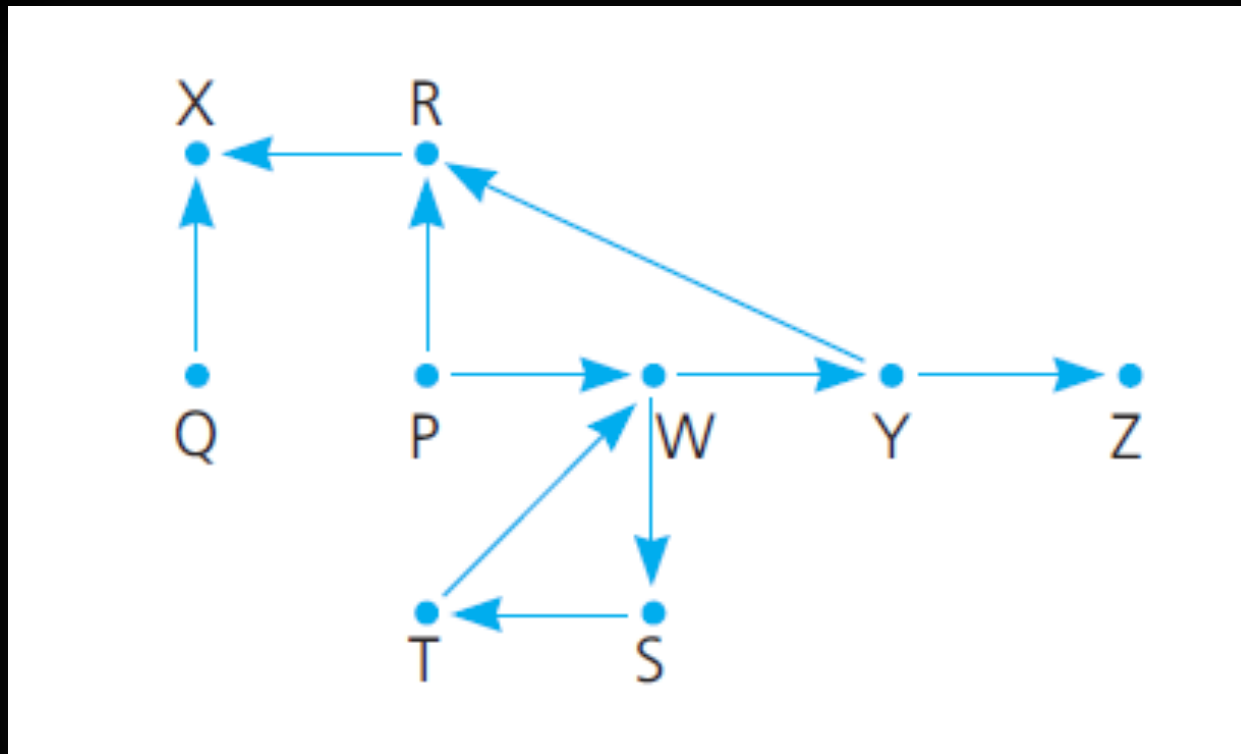


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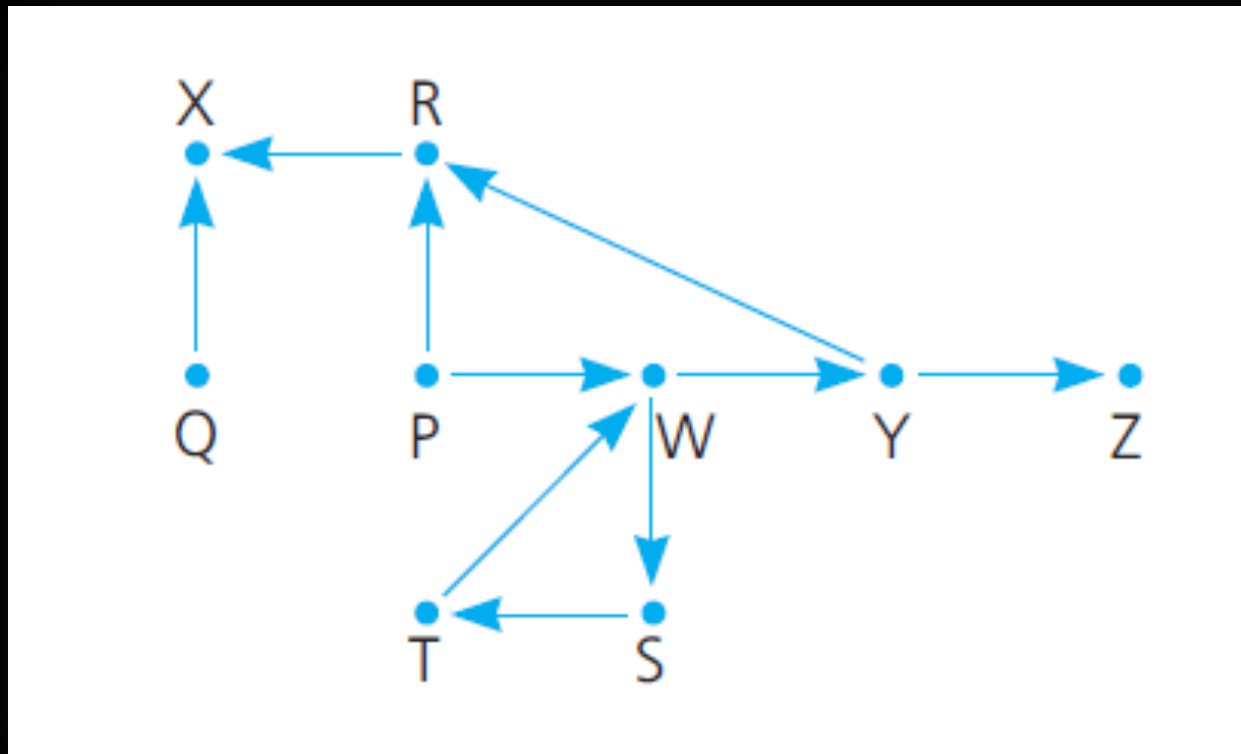


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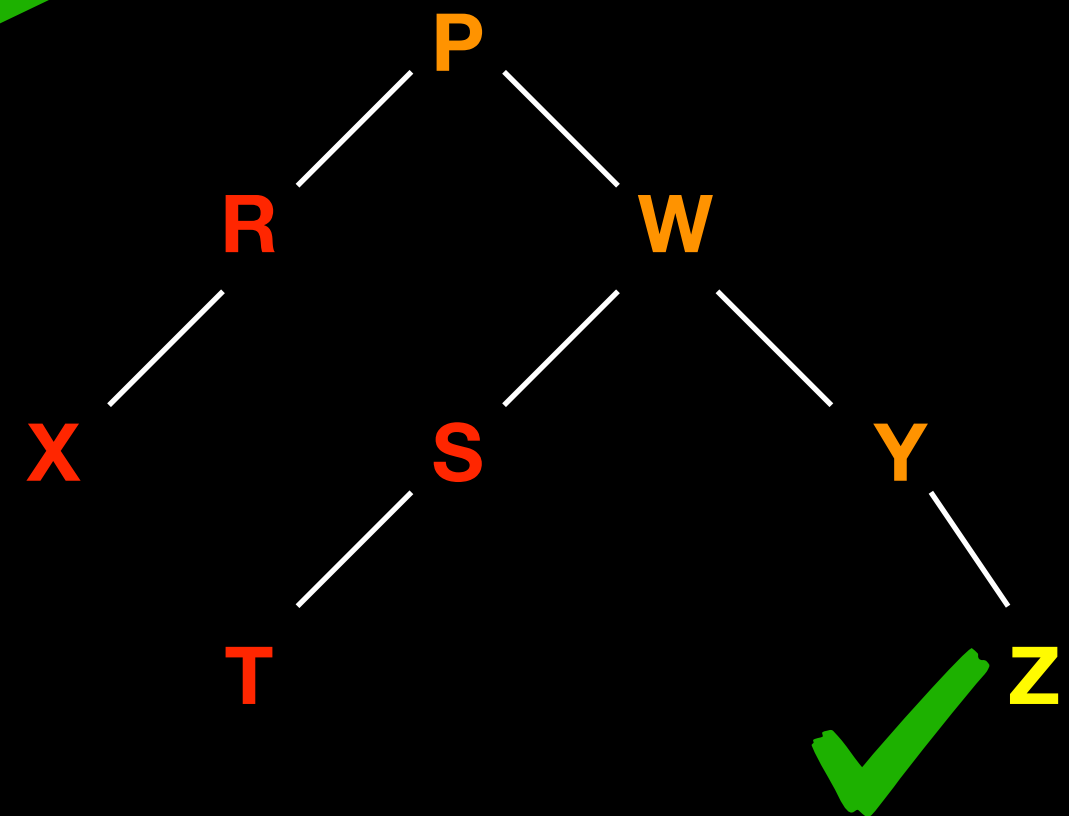
```
bool findPath(map, origin, destination)
```

**Origin = P** , **Destination = Z**



Don't get bogged down  
by what a map is.

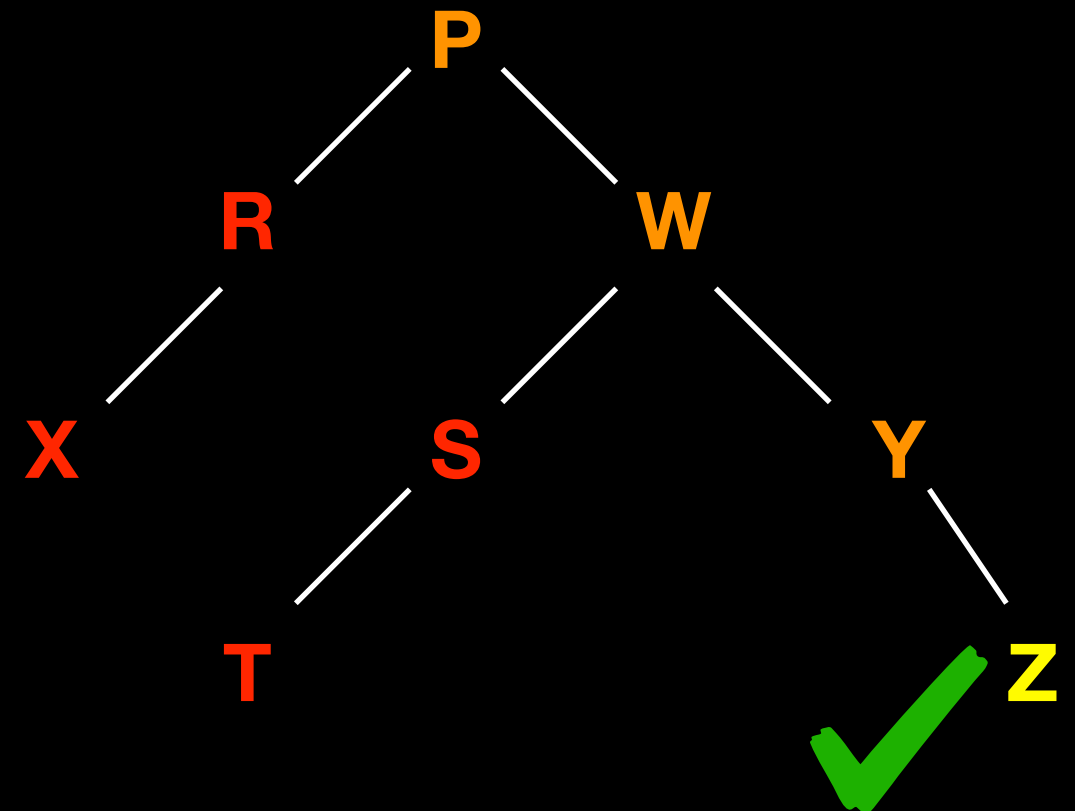
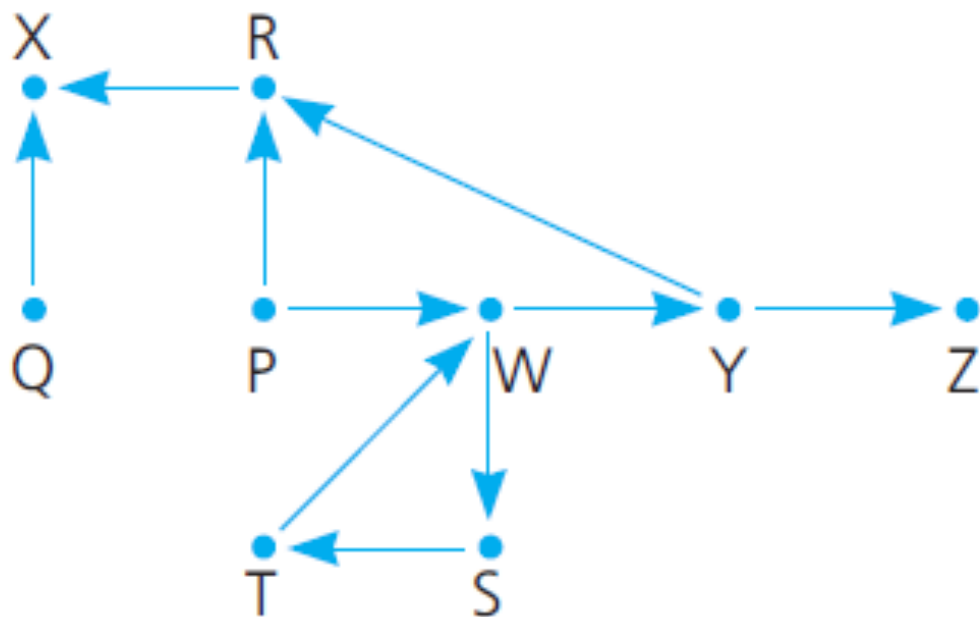
In design phase you  
know it's available and  
you can look up where  
you can go next from



# Lecture Activity

```
bool findPath(map, origin, destination)
{
    mark origin as visited in map
    if origin == destination
        return true
    else
        for each unvisited city C reachable from origin
            if findPath(map, C, destination) ← Recursive call
                return true
        return false //recursive backtracking
}
```

**Origin = P , Destination = Z**



# Find Permutations

Toy example to  
make initial  
observation

A	B	C	D
---	---	---	---

Order Matters!

A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

# Find Permutations

A	B	C	D
---	---	---	---

A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

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A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
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A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A



# Find Permutations

A	B	C	D
---	---	---	---

A	B	C	D	<b>B</b>	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	<b>B</b>	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	<b>B</b>	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	<b>B</b>	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	<b>B</b>	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	<b>B</b>	D	C	A	C	D	B	A	D	C	B	A

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A	B	C	D
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A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
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A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
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A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

# Find Permutations

A	B	C	D
---	---	---	---

Very similar to

000	100
001	101
010	110
011	111

A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

Lock the first letter  
For each letter you  
lock  
Permute the rest

# Find Permutations

A	B	C	D
---	---	---	---

A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

Lock the first letter  
For each letter you  
lock

Permute the rest

DECISION

RECURSION

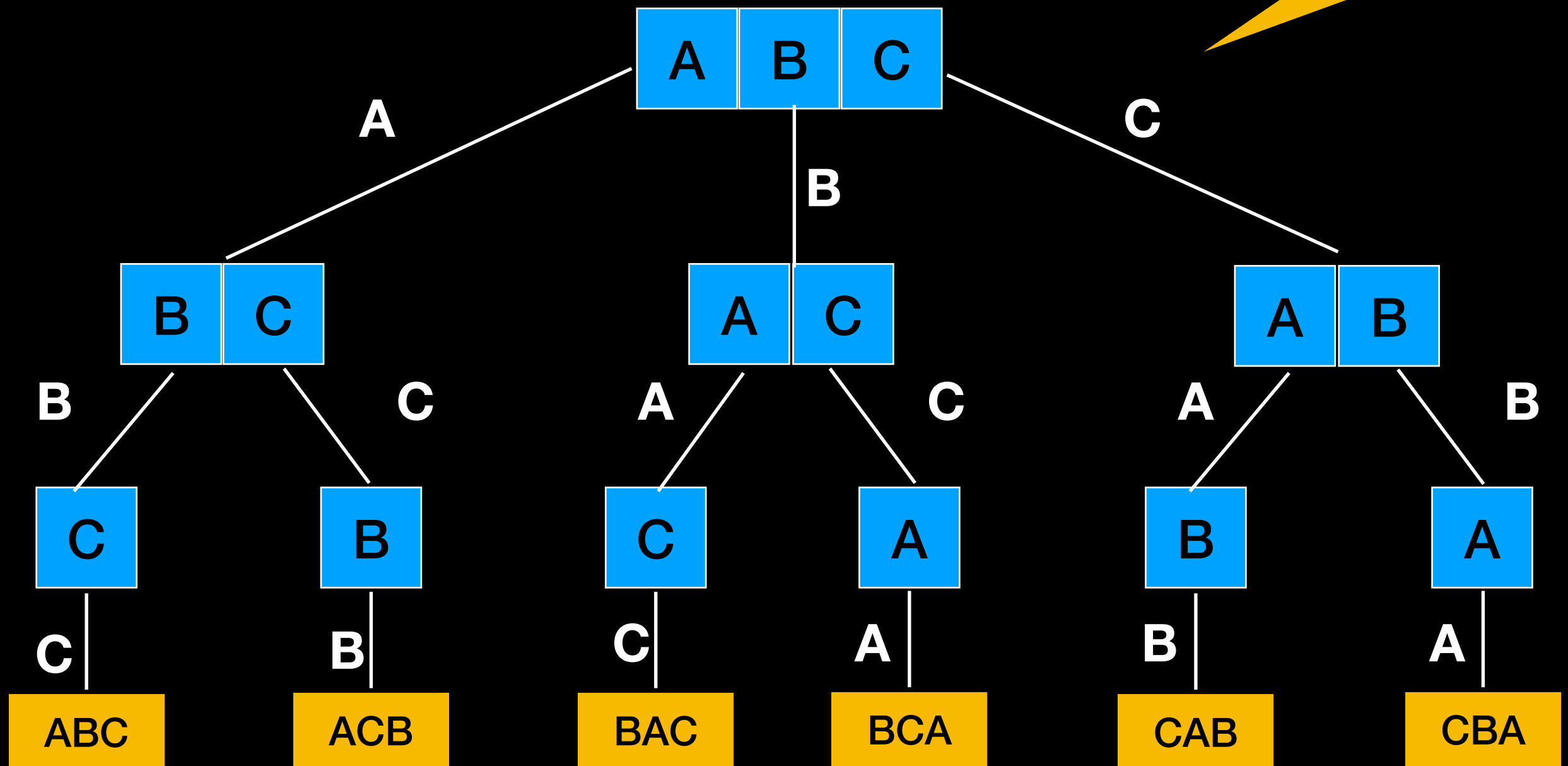
# Find Permutations

A	B	C	D
---	---	---	---

A	B	C	D	B	A	C	D	C	A	B	D	D	A	B	C
A	B	D	C	B	A	D	C	C	A	D	B	D	A	C	B
A	C	B	D	B	C	A	D	C	B	A	D	D	B	A	C
A	C	D	B	B	C	D	A	C	B	D	A	D	B	C	A
A	D	B	C	B	D	A	C	C	D	A	B	D	C	A	B
A	D	C	B	B	D	C	A	C	D	B	A	D	C	B	A

# Find Permutations

A Decision Tree



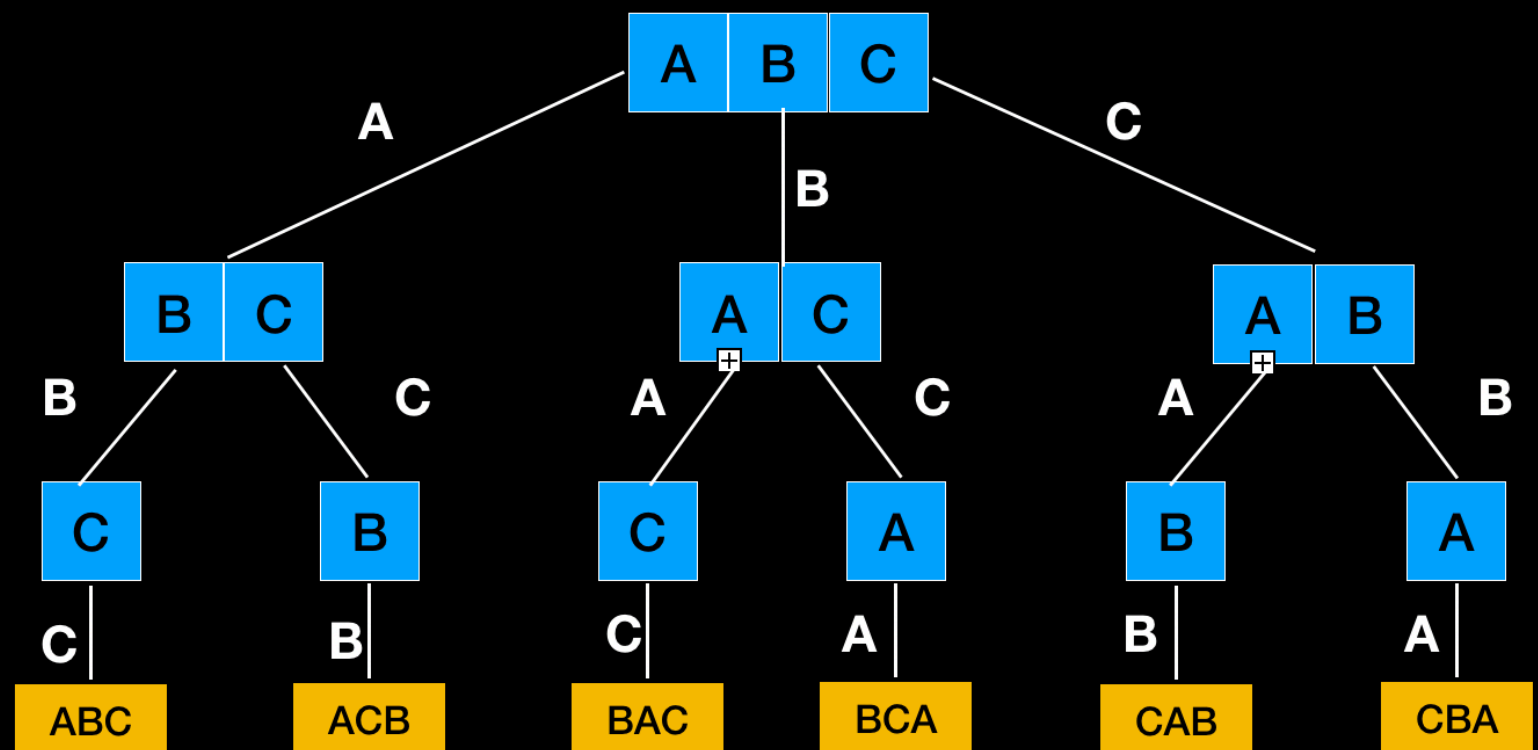


```

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    else
    {
        for (int i = l; i <= r; i++)
        {
            std::swap(str[l],str[i]); //swap other characters with current first
            → permuteStr(str, l+1, r);
            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

**A**BC  
**B**AC  
**C**BA



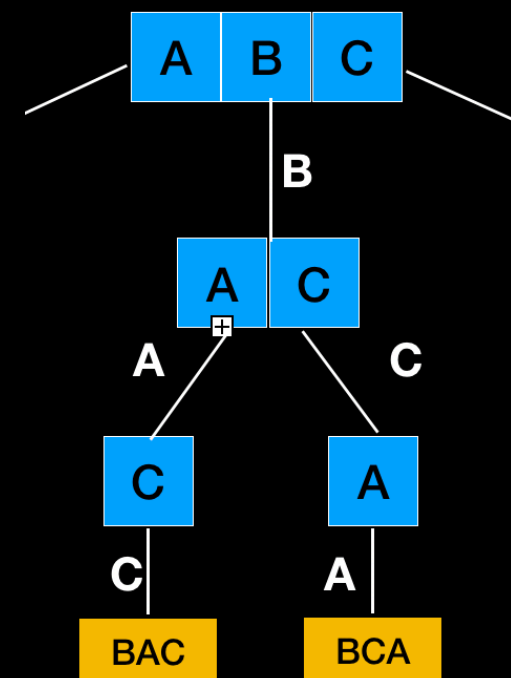
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            permuteStr(str, l+1, r);
            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

**ABC**

**i=1, l=0**



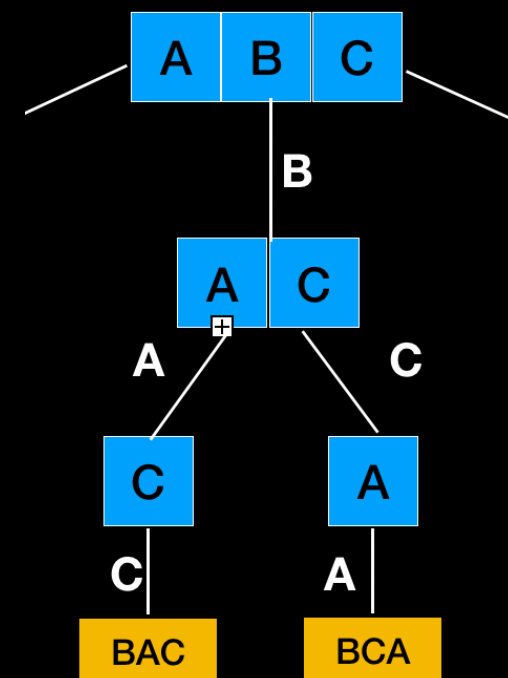
```

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              permuteStr(str, l+1, r);
              std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=1, l=0

**BAC**



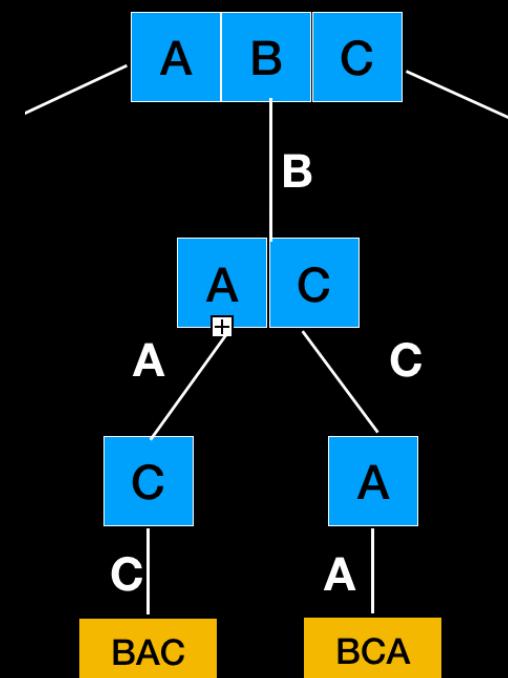
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            std::swap(str[l],str[i]); //swap other characters with current first
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            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=1, l=0

**BAC**



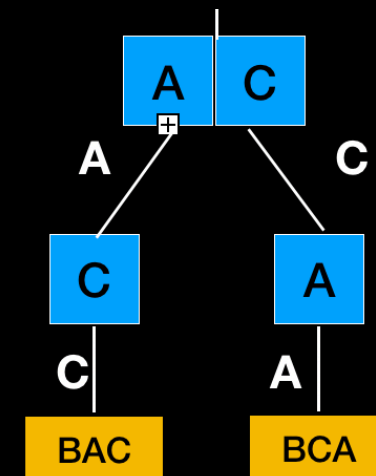
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            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=1, l=1

**BAC**



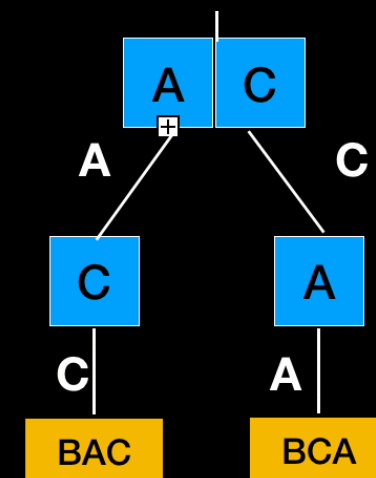
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```

i=1, l=1

**BAC**



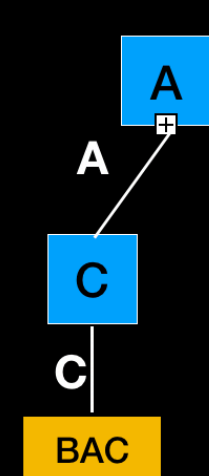
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        }
    }
}

```

i=1, l=1

**BAC**



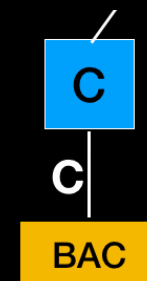
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    {
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        {
            std::swap(str[l],str[i]); //swap other characters with current first
            permuteStr(str, l+1, r);
            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=2, l=2

**BAC**





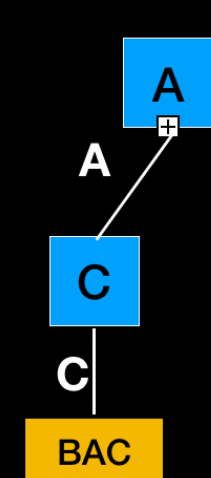
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```

i=1, l=1

**BAC**



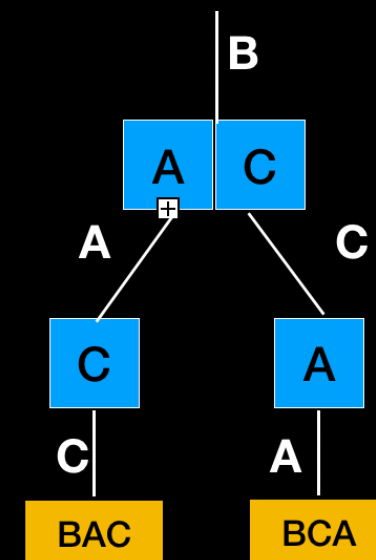
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```

i=2, l=1

**BCA**



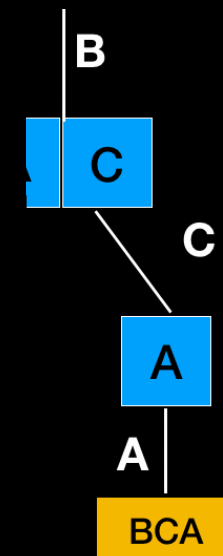
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```

i=2, l=1

**BCA**



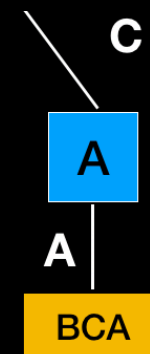
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            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=2, l=2

**BCA**



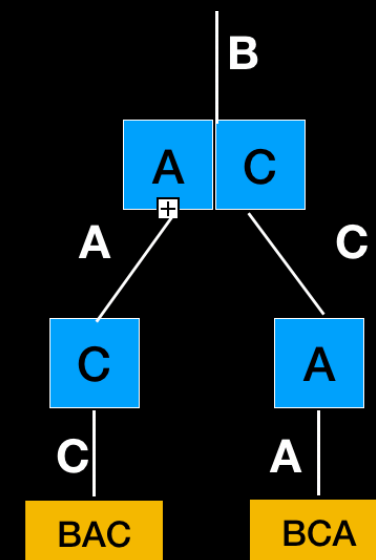
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            → std::swap(str[l],str[i]); //restore first char
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```

**i=2, l=1**

**BAC**



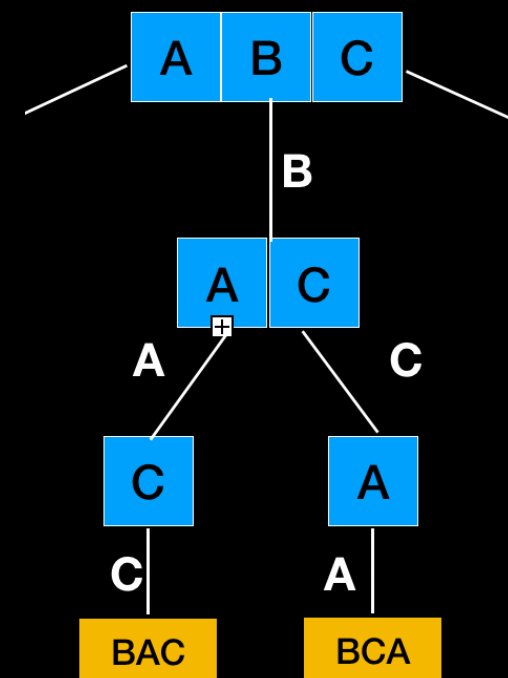
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        }
    }
}

```

i=1, l=0

ABC



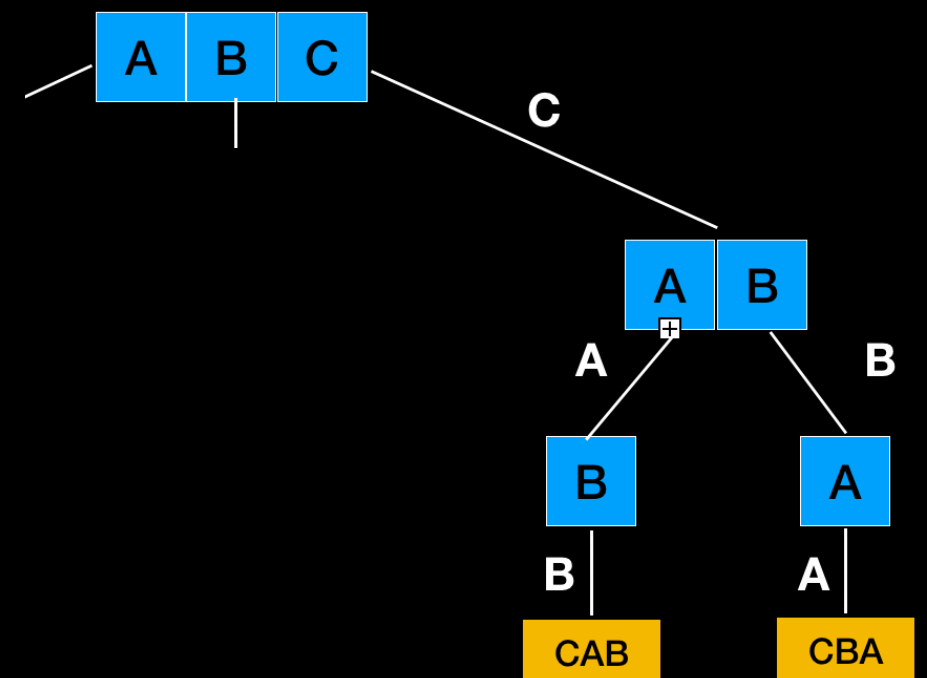
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            std::swap(str[l],str[i]); //restore first char
        }
    }
}

```

i=2, l=0

ABC



# Recursive Decision Tree

```
void exploreFrom(current_state, decisions_made) {  
    if (all decisions have been made) { //base case  
        output the result of the decisions we've made;  
    } else {  
        for (each decision we can make) {  
            → exploreFrom(result of making that decision,  
                           decisions_made + this_decision);  
        }  
    }  
}
```

Generally, if you can express a problem solution with a decision tree you can translate it into a recursive algorithm



# Find Combinations

A B C D

Order does  
Not matter!

{ }

A

A B

A B C

A B C D

B

A C

A B D

C

A D

A C D

D

B C

B C D

B D

C D

# Find Combinations of size 2

A B C D

Order does  
Not matter!

{ }

A

A B

A B C

A B C D

B

A C

A B D

C

A D

A C D

D

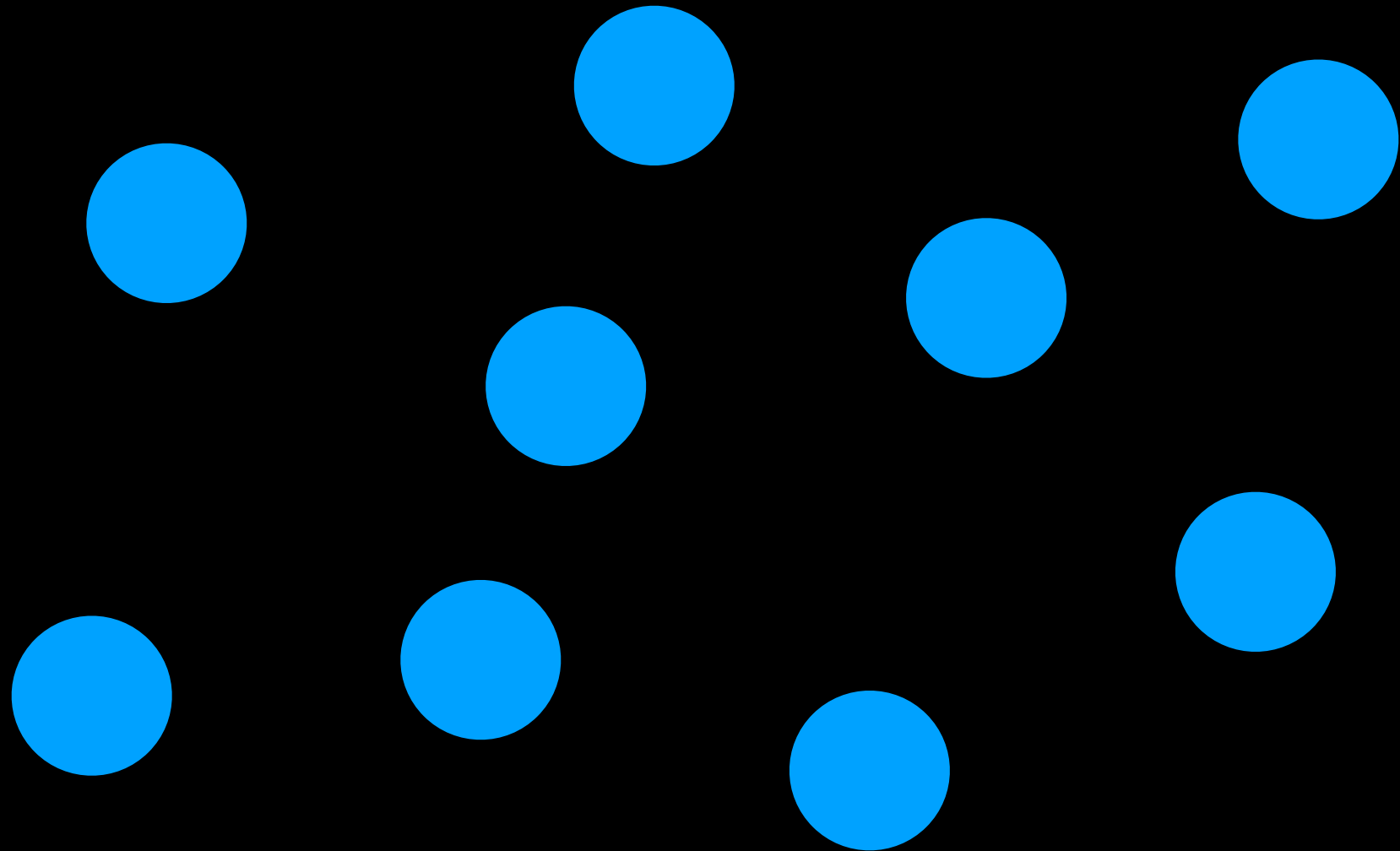
B C

B C D

B D

C D

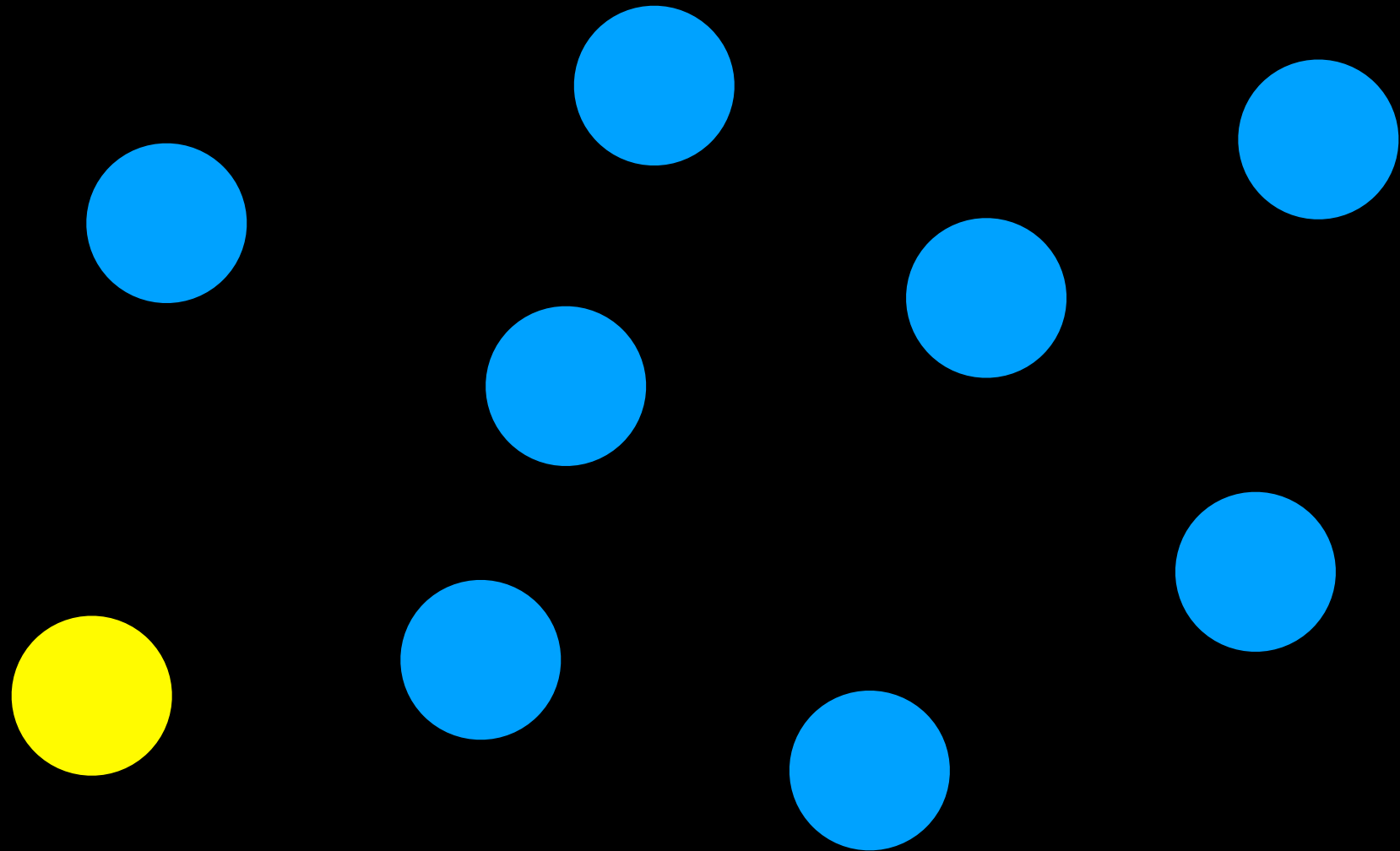
# Combinations (n choose k)



One way to choose 5 out of 9 is to  
**Exclude 1** and **choose 5 out of 8**

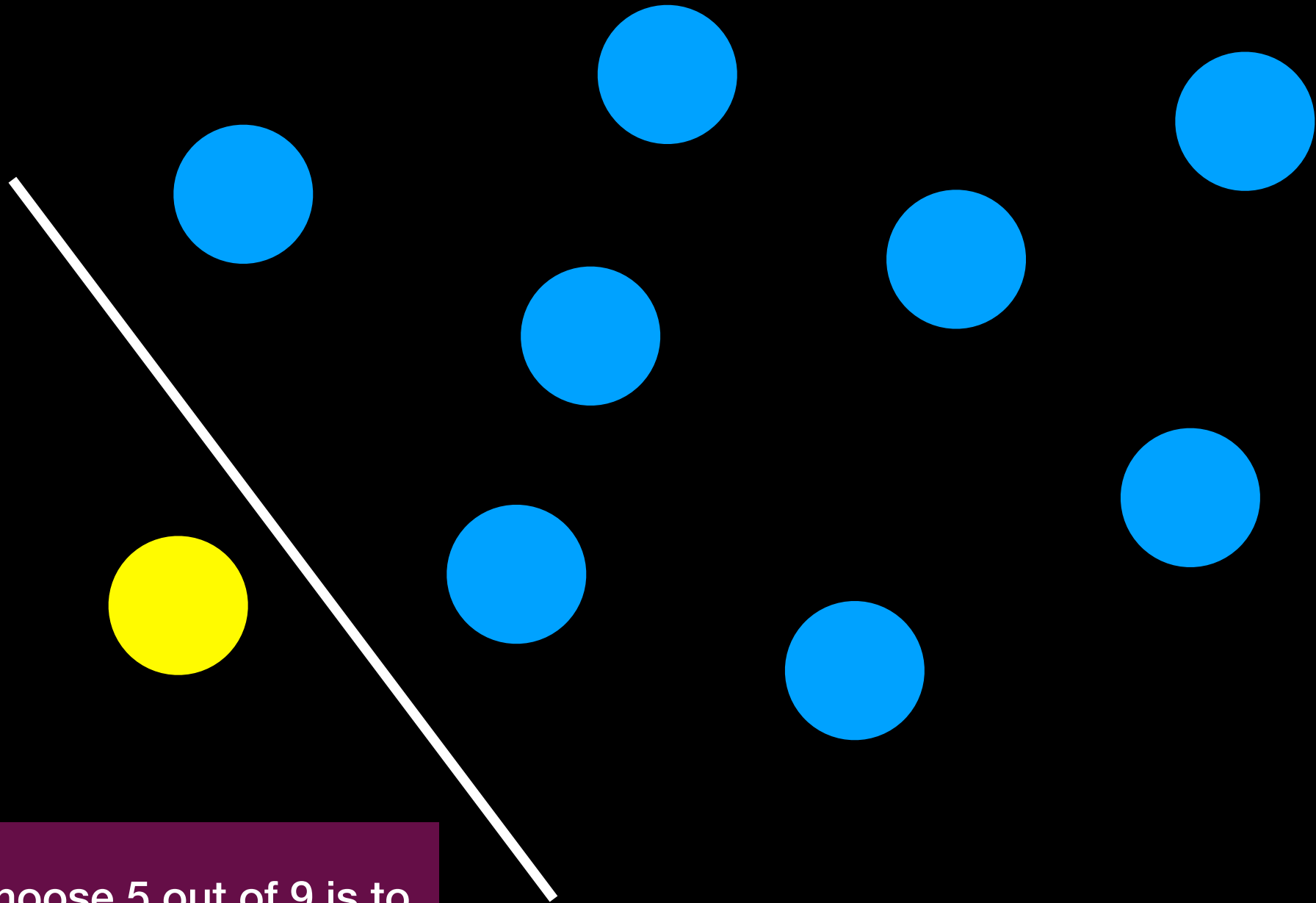
Start with toy problem  
to make observation

# Combinations (n choose k)



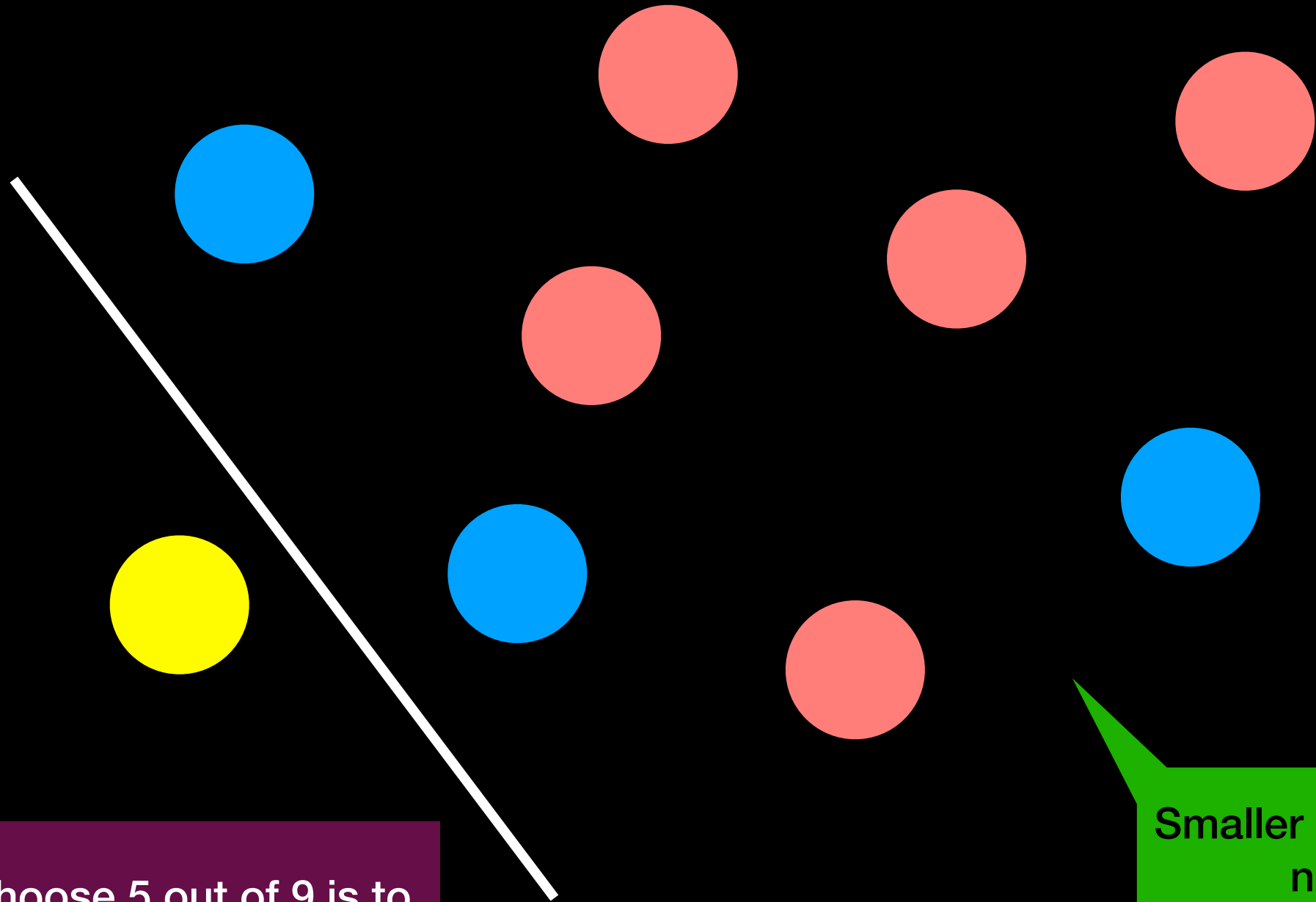
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# Combinations (n choose k)



One way to choose 5 out of 9 is to  
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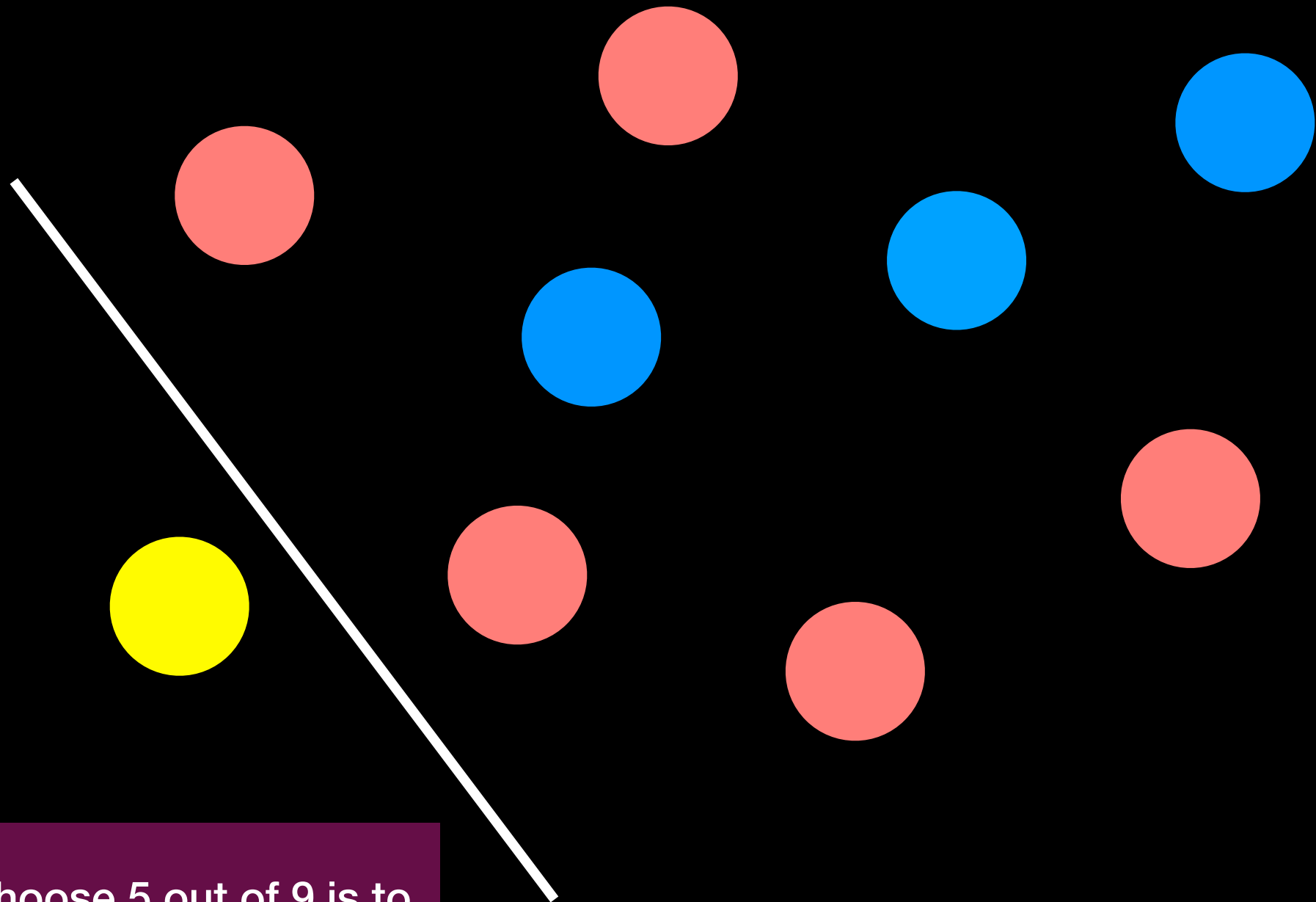
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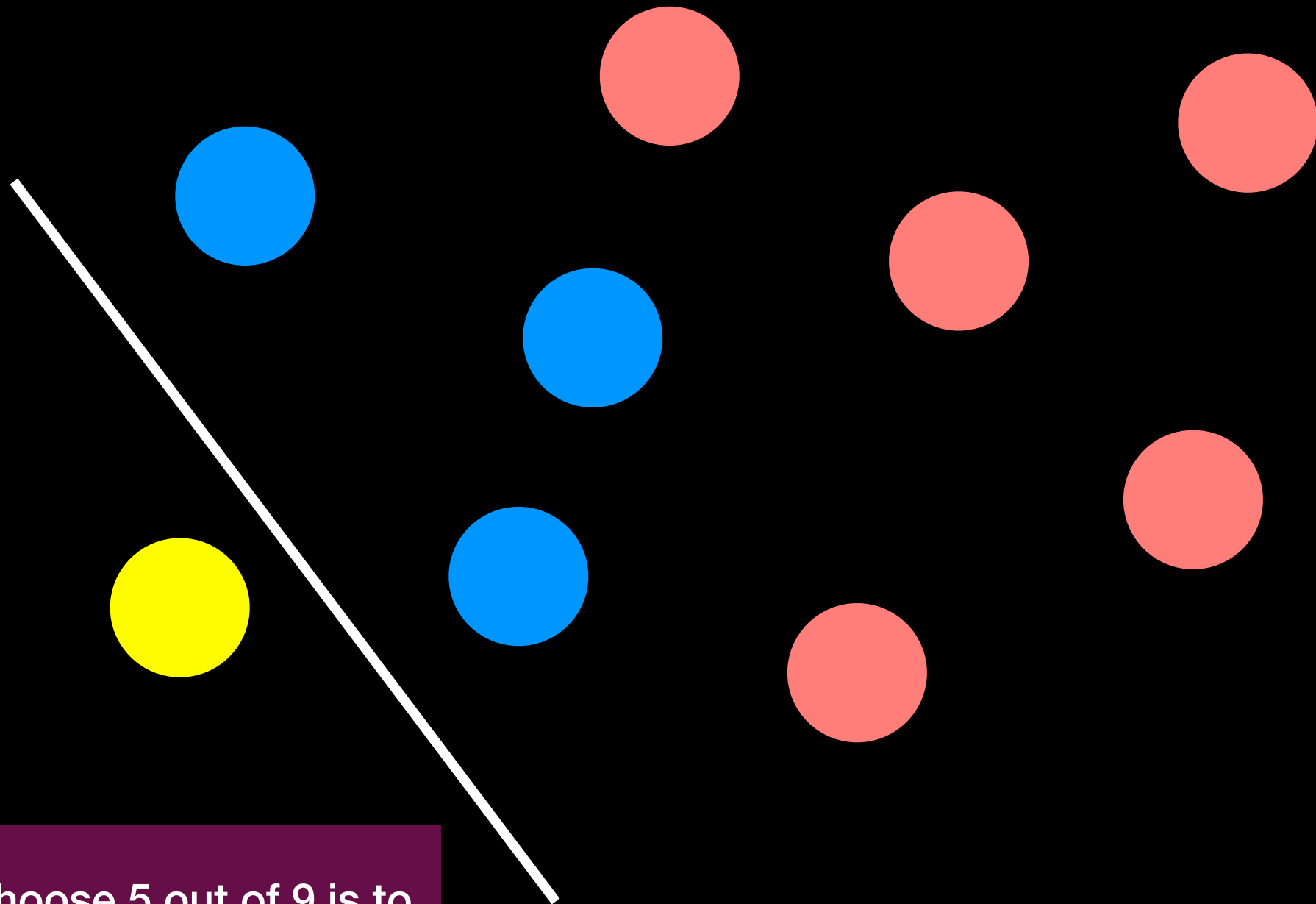
Smaller problem!  
n-1

# Combinations (n choose k)



One way to choose 5 out of 9 is to  
**Exclude 1** and **choose 5 out of 8**

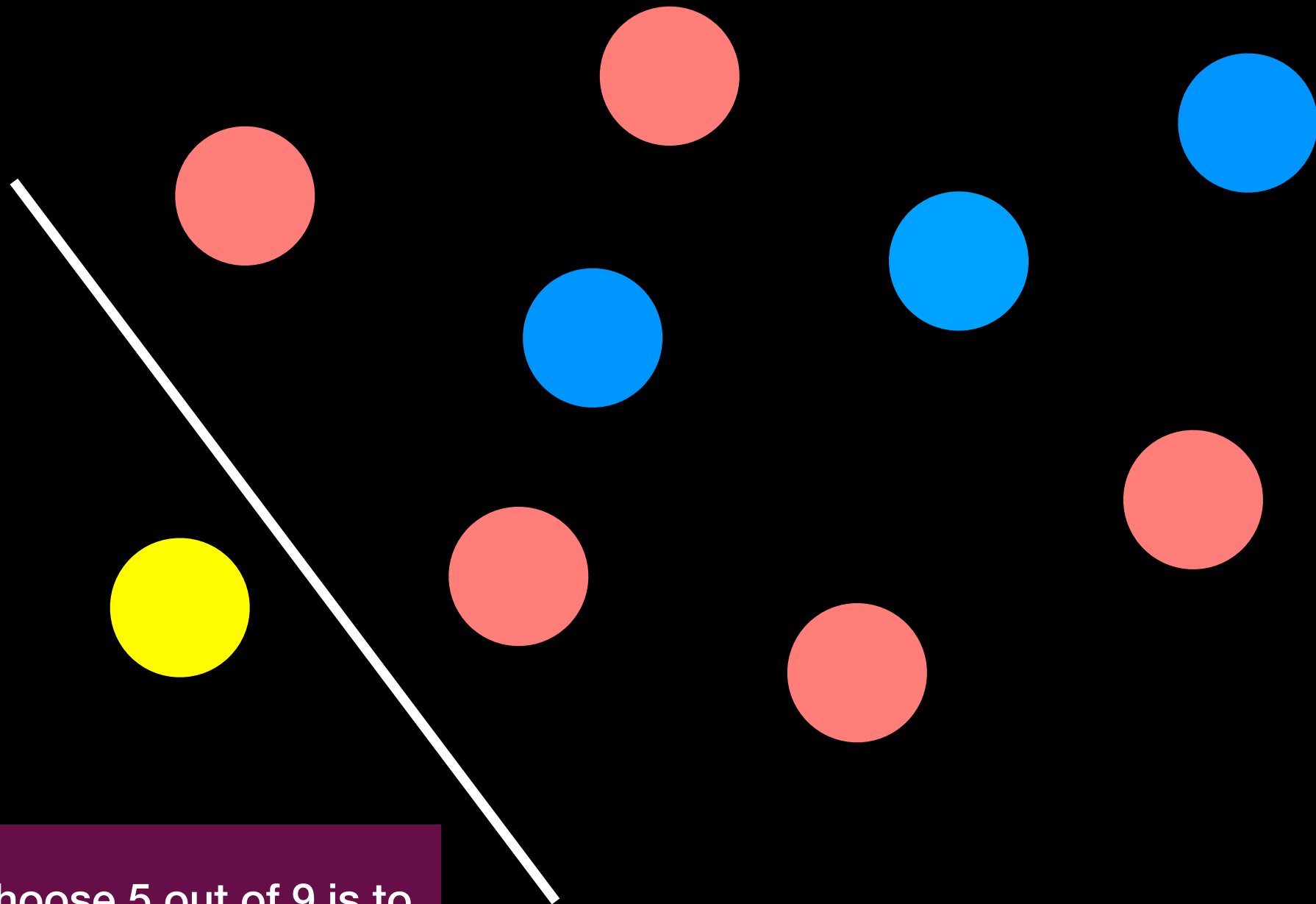
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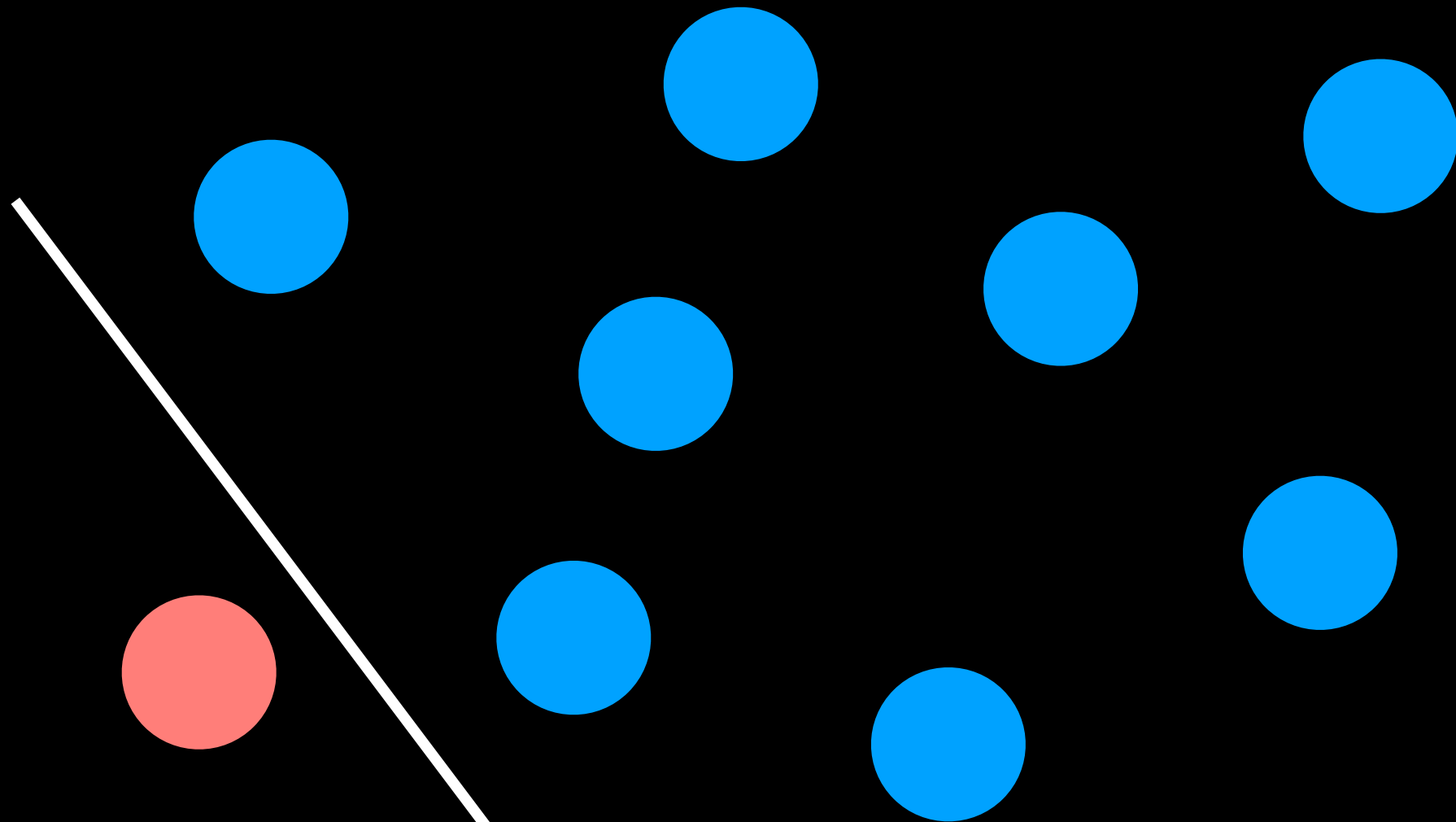


# Combinations (n choose k)



One way to choose 5 out of 9 is to  
**Exclude 1** and **choose 5 out of 8**

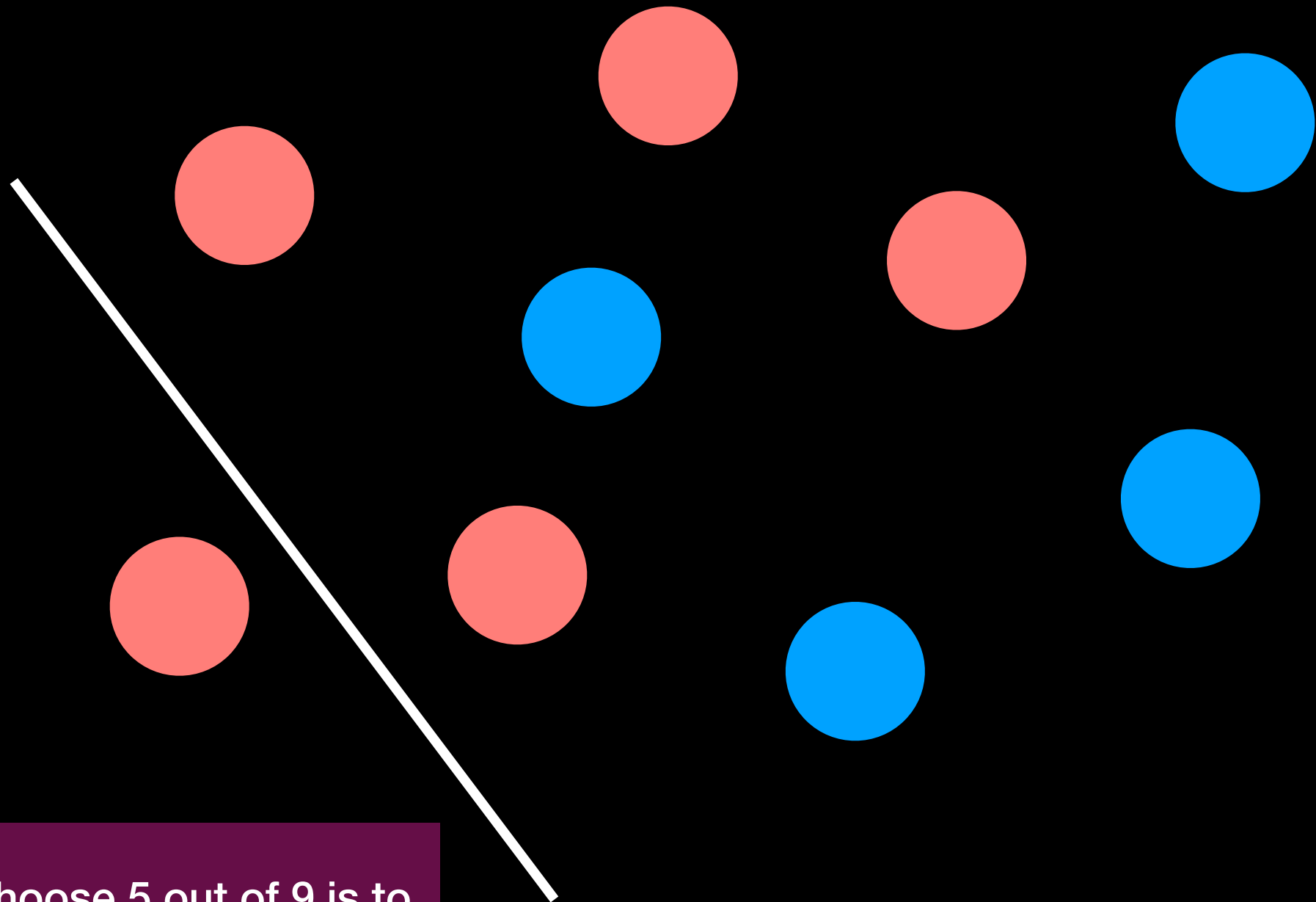
# Combinations (n choose k)



One way to choose 5 out of 9 is to  
Include 1 and choose 4 out of 8

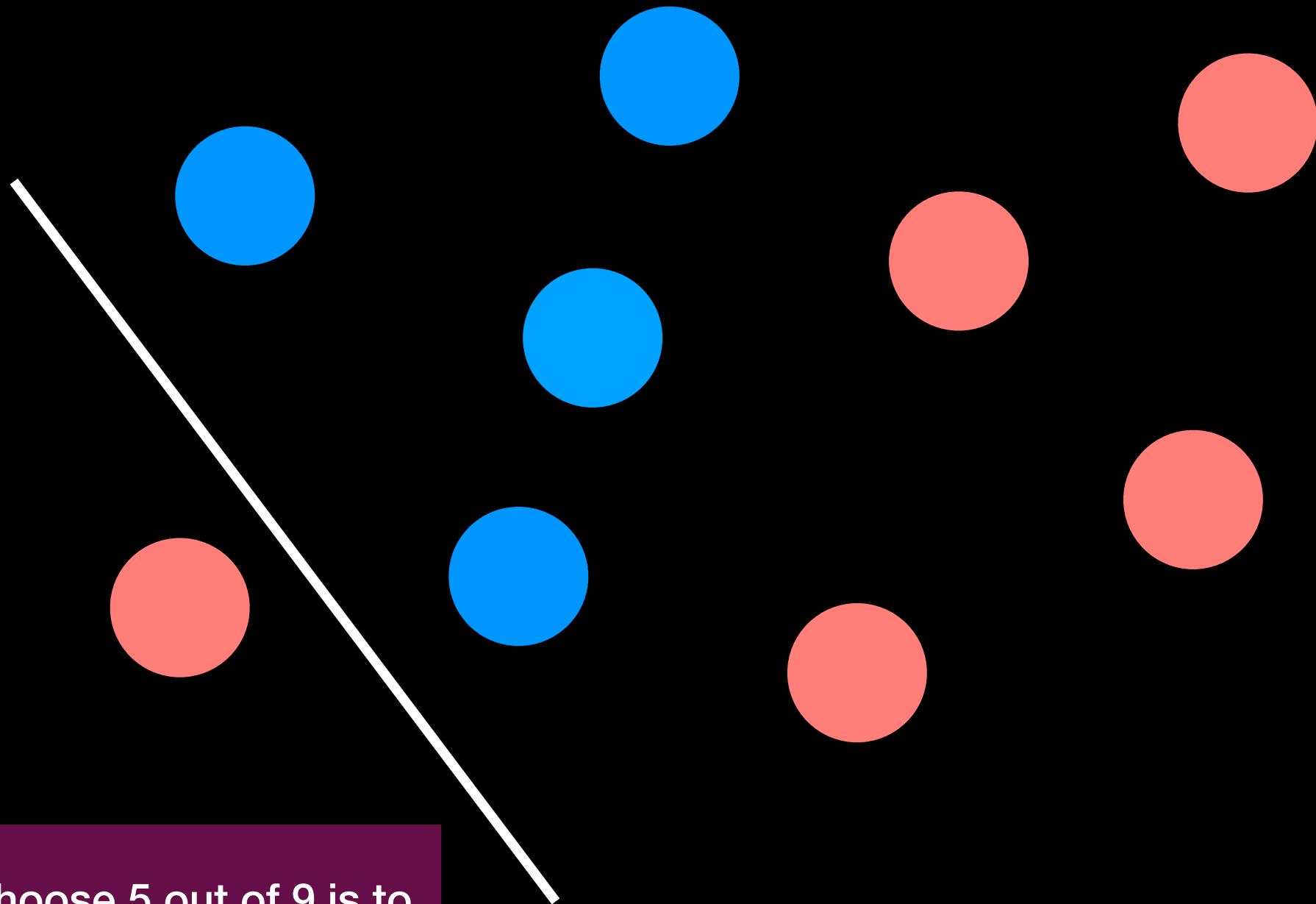
Need to make another  
observation

# Combinations (n choose k)



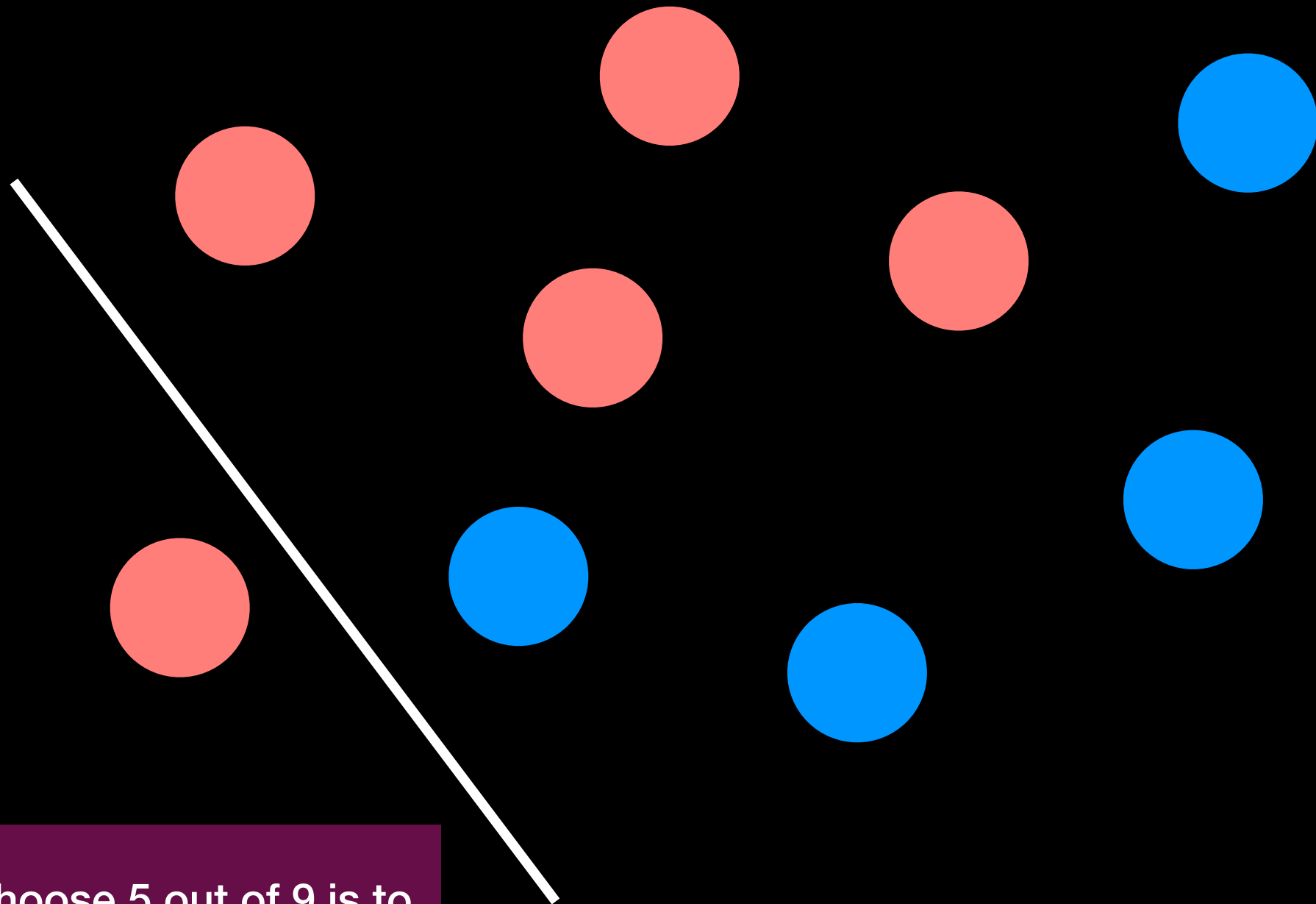
One way to choose 5 out of 9 is to  
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# Combinations (n choose k)



One way to choose 5 out of 9 is to  
Include 1 and choose 4 out of 8

# Combinations (n choose k)



One way to choose 5 out of 9 is to  
Include 1 and choose 4 out of 8

# Count Combinations

```
int countCombinations(int n, int k)
{
    if ( (k == 0) || (k == n) )
        return 1;
    else
        return countCombinations(n-1, k-1) +
               countCombinations(n-1, k);
}
```

Include one

Exclude one

Recursive algorithm for  
computing binomial coefficients

# How can you be sure it works???

You come up with an algorithm

You implement it

You test it

How can you be sure it will ALWAYS work???

# How can you be sure it works???

You come up with an algorithm

You implement it

You test it

How can you be sure it will ALWAYS work???

**PROVE IT!!!**



# Recursion and Induction

## Principle of Mathematical Induction:

Suppose you want to prove that a statement  $P(n)$  about an integer  $n$  is true for every positive integer  $n$ .

To prove that  $P(n)$  is true for all  $n \geq 1$ , do the following two steps:

- **Base Step:** Prove that  $P(1)$  is true.
- **Inductive Step:** Let  $k \geq 1$ . Assume  $P(k)$  is true, and prove that  $P(k + 1)$  is also true.

# Recursion and Induction

```
//a: nonzero real number, n: nonnegative integer
power(a, n)
{
    if (n = 0)
        return 1
    else
        return a * power(a, n - 1)
}
```

Prove by mathematical induction on  $n$  that the algorithm above is correct. We will show  $P(n)$  is true for all  $n \geq 0$ , where  
 $P(n)$ : For all nonzero real numbers  $a$ ,  $\text{power}(a, n)$  correctly computes  $a^n$ .

# Recursion and Induction

**Base step:** If  $n = 0$ , the first step of the algorithm tells us that  $\text{power}(a, 0) = 1$ . This is correct because  $a^0 = 1$  for every nonzero real number  $a$ , so  $P(0)$  is true.

**Inductive step:**

Let  $k \geq 0$ .

**Inductive hypothesis:**  $\text{power}(a, k) = a^k$ , for all  $a \neq 0$ .

We must show next that  $\text{power}(a, k+1) = a^{k+1}$ .

Since  $k + 1 > 0$  the algorithm sets

$\text{power}(a, k + 1) = a * \text{power}(a, k)$

By inductive hypotheses  $\text{power}(a, k) = a^k$

**so**  $\text{power}(a, k + 1) = a * \text{power}(a, k) = a * a^k = a^{k+1}$

# Exam Drill

Write a recursive function that returns true if the input string is a palindrome (same when reversed)

# Exam Drill

Write a recursive function that returns true if the input string is a palindrome (same when reversed)

```
bool isPalindrome(std::string s)
{
    if(s.length() == 0 || s.length() == 1) //base case
        return true; //empty string or string of size 1 are palindrome
    if(s[0] == s[s.length()-1]) //if first and last char are same
        //check substring leaving out first and last character
        return isPalindrome(s.substr(1, s.length()-2));
    return false; //not palindrome
}
```

# Exam Drill

Write a recursive function for the fibonacci numbers  
where  $f(n) = f(n-1) + f(n-2)$

# Exam Drill

Write a recursive function for the fibonacci numbers  
where  $f(n) = f(n-1) + f(n-2)$

```
int fib(int n)
{
    if (n <= 1) //base case
        return n;
    return fib(n-1) + fib(n-2);
}
```

# Exam Drill

Write a recursive function to find the max value in an array of integers



# Exam Drill

Write a recursive function to find the max value in an array of integers

```
int findMax(int* a, int index) {  
    if (index > 0)  
        return std::max(a[index], findMax(a, index-1));  
    else  
        return a[0];  
}
```

# Exam Drill

Write a **recursive** function that finds a particular item in a **sorted** array (we will look at this algorithm after the midterm)