

# Even More Counting

CSE 312 Spring 24  
Lecture 3

# Announcements

HW 1 is out! Due Wednesday.

Office hours started yesterday! Visit now before others start on the homework.

Also, please start on the homework early.

# Announcements

There's an optional (online) textbook.

It's linked on the webpage (under the resources tab).

Useful if you want a different perspective.

Occasional differences in notation/vocabulary, but still useful!

# Outline

## So Far

Sum and Product Rules

Combinations (order doesn't matter) and Permutations (order does matter)

Introduce ordering and remove it to make calculations easier

## This Time

Some Proofs by counting two ways

Binomial Theorem

Principle of Inclusion-Exclusion

# Overcounting

How many anagrams are there of SEATTLE  
(an anagram is a rearrangement of letters).

It's not 7! That counts SEATTLE and SEATTLE as different things!  
I swapped the Es (or maybe the Ts)

# Overcounting

How many anagrams are there of SEATTLE

Pretend the order of the Es (and Ts) relative to each other matter (that SEATTLE and SEATTLE are different)

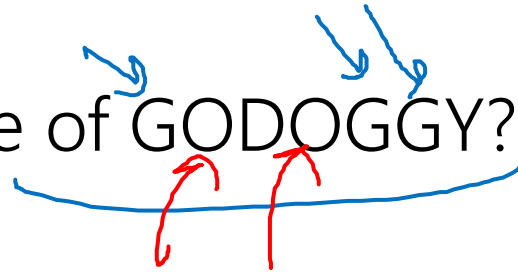
How many arrangements of SEATTLE?  $7!$

How have we overcounted? Es relative to each other and Ts relative to each other  $2! \cdot 2!$

Final answer  $\frac{7!}{2! \cdot 2!}$

# Overcounting

How many anagrams are there of GODOGGY?



$$\frac{7!}{3! \cdot 2!}$$

# Overcounting

How many anagrams are there of GODOGGY?

$$\frac{7!}{2!3!}$$

$$\binom{7}{3,2}$$

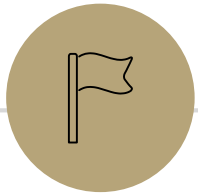
One more piece of notation – “multinomial coefficient”

$\binom{7}{2,3}$  is alternate notation for  $\frac{7!}{2!3!}$ .

In general:  $\binom{n}{k_1, k_2, \dots, k_\ell} = \frac{n!}{k_1! \cdot k_2! \cdot \dots \cdot k_\ell!}$

Popular notation among mathematicians.





# Combination Facts

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# Some Facts about combinations

Symmetry of combinations:  $\binom{n}{k} = \binom{n}{n-k}$

Pascal's Rule:  $\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$

# Two Proofs of Symmetry

Proof 1: By algebra

$$\binom{n}{k} = \frac{n!}{\underline{k!(n-k)!}} \quad \text{Definition of Combination}$$

$$= \frac{n!}{\underline{(n-k)!k!}} \quad \text{Algebra (commutativity of multiplication)}$$

$$= \binom{n}{\underline{n-k}} \quad \text{Definition of Combination}$$

$$n - [n - k] = k$$

$$\frac{n!}{k! \cdot (n-k)!}$$

$$\frac{n!}{(n-k)! \cdot k!}$$

# Two Proofs of Symmetry

Wasn't that a great proof.

Airtight. No disputing it.

Got to say "commutativity of multiplication."

But...do you know *why*? Can you *feel* why it's true?

# Two Proofs of Symmetry

Suppose you have  $n$  people, and need to choose  $k$  people to be on your team. We will count the number of possible teams two different ways.

**Way 1:** We choose the  $k$  people to be on the team. Since order doesn't matter (you're on the team or not), there are  $\binom{n}{k}$  possible teams.

**Way 2:** We choose the  $n - k$  people to NOT be on the team. Everyone else is on it. Since order again doesn't matter, there are  $\binom{n}{n-k}$  possible ways to choose the team.

Since we're counting the same thing, the numbers must be equal.

$$\text{So } \binom{n}{k} = \binom{n}{n-k}.$$

# Pascal's Rule: $\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$

$$\begin{aligned} \binom{n-1}{k-1} + \binom{n-1}{k} &= \frac{(n-1)!}{(k-1)!(n-1-[k-1])!} + \frac{(n-1)!}{k!(n-1-k)!} && \text{definition of combination} \\ &= \frac{(n-1)!}{(k-1)!(n-k)!} + \frac{(n-1)!}{k!(n-k-1)!} && \text{subtraction} \\ &= \frac{[(n-1)!k!(n-k-1)!] + [(n-1)!(k-1)!(n-k)!]}{k!(k-1)!(n-k)!(n-k-1)!} && \text{Find a common denominator} \\ &= \frac{(n-1)!(k-1)!(n-k-1)! [k + (n-k)]}{k!(k-1)!(n-k)!(n-k-1)!} && \text{factor out common terms} \\ &= \frac{(n-1)! [k + (n-k)]}{k!(n-k)!} && \text{Cancel } (k-1)!(n-k-1)! \\ &= \frac{(n-1)! \cdot n}{k!(n-k)!} = \frac{n!}{k!(n-k)!} && \text{Algebra} \\ &= \binom{n}{k} && \text{Definition of combination} \end{aligned}$$

Pascal's Rule:  $\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$

You and  $n - 1$  other people are trying out for a  $k$  person team. How many possible teams are there?

**Way 1:** There are  $n$  people total, of which we're choosing  $k$  (and since it's a team order doesn't matter)  $\binom{n}{k}$ .

**Way 2:** There are two types of teams. Those for which you make the team, and those for which you didn't make the team.

If you do make the team, then  $k - 1$  of the other  $n - 1$  also make it.

If you don't make the team,  $k$  of the other  $n - 1$  also make it.

Overall, by sum rule,  $\binom{n-1}{k-1} + \binom{n-1}{k}$ .

Since we're computing the same number two different ways, they must be equal. So:  $\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$

# Takeaways

Formulas for factorial, permutations, combinations.

A useful trick for counting is to pretend order matters, then account for the overcounting at the end (by dividing out repetitions)

When trying to prove facts about counting, try to have each side of the equation count the same thing.

Much more fun and much more informative than just churning through algebra.



# Binomial Theorem



In high school you probably memorized

$$(x + y)^2 = x^2 + 2xy + y^2$$

$$\text{And } (x + y)^3 = x^3 + 3x^2y + 3xy^2 + y^3$$

$$\frac{3!}{2!1!}$$

The Binomial Theorem tells us what happens for every  $n$ :

## The Binomial Theorem

$$(x + y)^n = \sum_{i=0}^n \binom{n}{i} x^i y^{n-i}$$

# Some intuition

## The Binomial Theorem

$$(x + y)^n = \sum_{i=0}^n \binom{n}{i} x^i y^{n-i}$$

Intuition: Every monomial on the right-hand-side has either  $x$  or  $y$  from each of the terms on the left.

How many copies of  $x^i y^{n-i}$  do you get? Well how many ways are there to choose  $i$   $x$ 's and  $n - i$   $y$ 's?  $\binom{n}{i}$ .

Formal proof? Induction!

# So What?

Well...if you saw it before, now you have a better understanding now of why it's true.

There are also a few cute applications of the binomial theorem to proving other theorems (usually by plugging in numbers for  $x$  and  $y$ ) – you'll do one on HW1.

For example, set  $x = 1$  and  $y = 1$  then

$$\underline{2^n} = (1 + 1)^n = \sum_{i=0}^n \binom{n}{i} \underline{1^i 1^{n-i}} = \sum_{i=0}^n \binom{n}{i}.$$

i.e. if you sum up binomial coefficients, you get  $2^n$ . Exercise: reprove this equation (directly) with a combinatorial proof (where have we seen  $2^n$  recently?)



# Example

How many length 5 strings over the alphabet  $\{a, b, c, \dots, z\}$  contain:

Exactly 2 'a's OR

Exactly 1 'b' OR

No 'x's

For what  $A, B, C$  do we want  $|A \cup B \cup C|$ ?

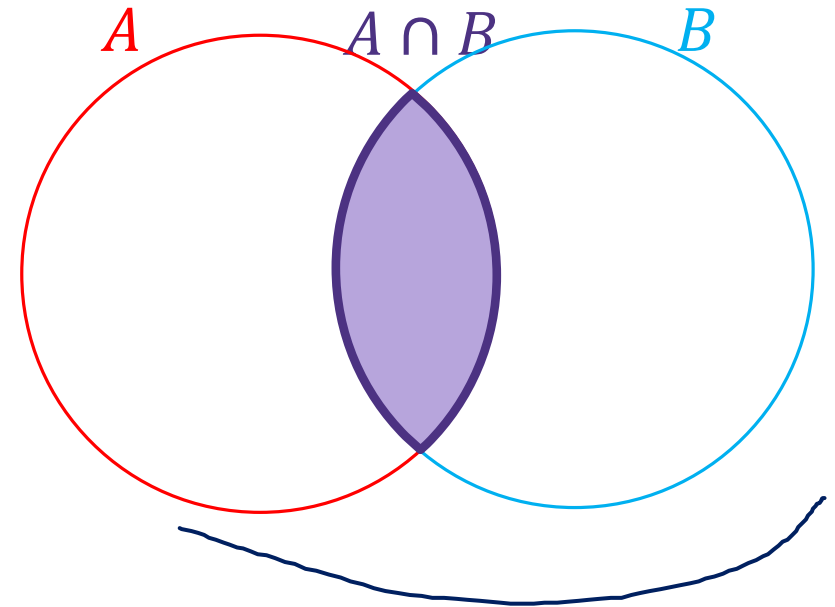
# Principle of Inclusion-Exclusion

The sum rule says when  $A$  and  $B$  are disjoint (no intersection), then  $|A \cup B| = |A| + |B|$ .

What about when  $A$  and  $B$  aren't disjoint?

For two sets:

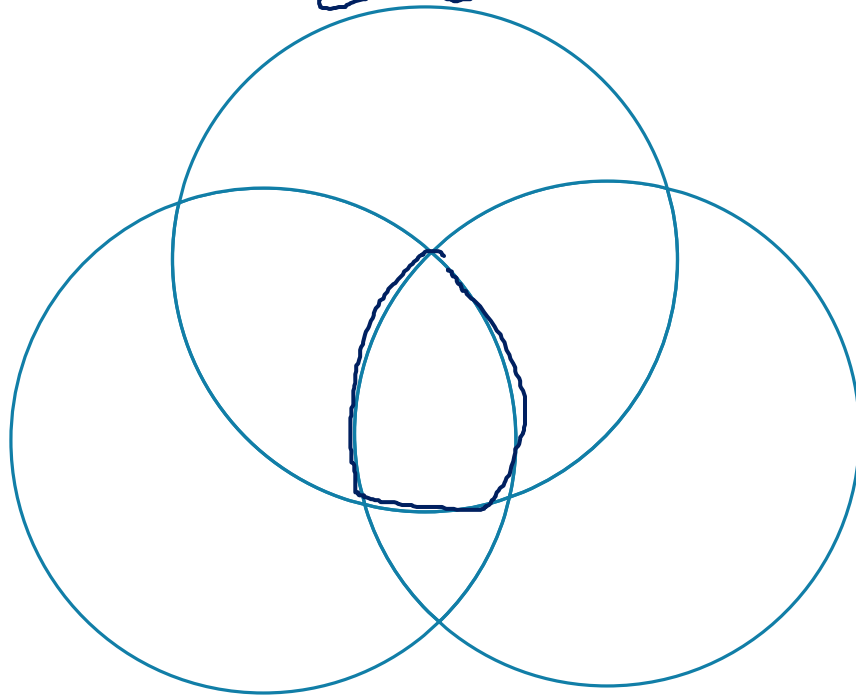
$$|A \cup B| = |A| + |B| - |A \cap B|$$



# Principle of Inclusion-Exclusion

For three sets:

$$|A \cup B \cup C| = |A| + |B| + |C| - |A \cap B| - |B \cap C| - |A \cap C| + |A \cap B \cap C|$$



# Example

How many length 5 strings over the alphabet  $\{a, b, c, \dots, z\}$  contain:

Exactly 2 'a's OR

Exactly 1 'b' OR

No 'x's

For what  $A, B, C$  do we want  $|A \cup B \cup C|$ ?



# In general:

$$|A_1 \cup A_2 \cup \dots \cup A_n| =$$

$$|A_1| + |A_2| + \dots + |A_n|$$

$$- (|A_1 \cap A_2| + |A_1 \cap A_3| + \dots + |A_1 \cap A_n| + |A_2 \cap A_3| + \dots + |A_{n-1} \cap A_n|)$$

$$+ (|A_1 \cap A_2 \cap A_3| + \dots + |A_{n-2} \cap A_{n-1} \cap A_n|)$$

- ...

$$+ (-1)^{n+1} |A_1 \cap A_2 \cap \dots \cap A_n|$$

Add the individual sets, subtract all pairwise intersections, add all three-wise intersections, subtract all four-wise intersections, ..., [add/subtract] the  $n$ -wise intersection.

# Example

How many length 5 strings over the alphabet  $\{a, b, c, \dots, z\}$  contain:

Exactly 2 'a's OR

Exactly 1 'b' OR

No 'x's

$A = \{\text{length 5 strings that contain exactly 2 'a's}\}$

$B = \{\text{length 5 strings that contain exactly 1 'b's}\}$

$C = \{\text{length 5 strings that contain no 'x's'}\}$

$|A| = \binom{5}{2} \cdot 25^3$  (need to choose which "spots" are 'a' and remaining string)

$|B| = \binom{5}{1} \cdot 25^4$

$|C| = 25^5$

# Example

How many length 5 strings over the alphabet  $\{a, b, c, \dots, z\}$  contain:

Exactly 2 'a's OR

Exactly 1 'b' OR

No 'x's

$$\begin{aligned} A &= \{\text{length 5 strings that contain exactly 2 'a's}\} & |A| &= \binom{5}{2} \cdot 25^3 \\ B &= \{\text{length 5 strings that contain exactly 1 'b's}\} & |B| &= \binom{5}{1} \cdot 25^3 \\ C &= \{\text{length 5 strings that contain no 'x's'}\} & |C| &= 25^5 \end{aligned}$$

$$|A \cap B| = \binom{5}{2} \cdot \binom{3}{1} \cdot 24^2 \text{ (choose 'a' spots, 'b' spot, remaining chars)}$$

$$|A \cap C| = \binom{5}{2} \cdot 24^3 \text{ (choose 'a' spots, remaining [non-'x'] chars)}$$

$$|B \cap C| = \binom{5}{1} \cdot 24^4$$

$$|A \cap B \cap C| = \binom{5}{2} \cdot \binom{3}{1} \cdot 23^2 \text{ (choose 'a' spots, 'b' spot, remaining [non-'x'] chars)}$$

# Example

How many length 5 strings over the alphabet  $\{a, b, c, \dots, z\}$  contain:

Exactly 2 'a's OR

Exactly 1 'b' OR

No 'x's

$$|A| = \binom{5}{2} \cdot 25^3$$

$$|B| = \binom{5}{1} \cdot 25^4$$

$$|C| = 25^5$$

$$|A \cap B| = \binom{5}{2} \cdot \binom{3}{1} \cdot 24^2$$

$$|A \cap C| = \binom{5}{2} \cdot 24^3$$

$$|B \cap C| = \binom{5}{1} \cdot 24^4$$

$$|A \cap B \cap C| = \binom{5}{2} \cdot \binom{3}{1} \cdot 23^2$$

$$|A \cup B \cup C| =$$

$$= |A| + |B| + |C| - |A \cap B| - |A \cap C| - |B \cap C| + |A \cap B \cap C|$$

$$= \binom{5}{2} \cdot 25^3 + \binom{5}{1} \cdot 25^4 + 25^5 - |A \cap B| - |A \cap C| - |B \cap C| + |A \cap B \cap C|$$

$$= 11,875,000 - |A \cap B| - |A \cap C| - |B \cap C| + |A \cap B \cap C|$$

$$= 11,875,000 - \binom{5}{2} \cdot \binom{3}{1} \cdot 24^2 - \binom{5}{2} \cdot 24^3 - \binom{5}{1} \cdot 24^4 + |A \cap B \cap C|$$

$$= 11,875,000 - 1,814,400 + |A \cap B \cap C|$$

$$= 10,060,600 + |A \cap B \cap C|$$

$$= 10,060,600 + \binom{5}{2} \cdot \binom{3}{1} \cdot 23^2$$

$$= 10,060,600 + 15,870$$

$$= 10,076,470$$

# Practical tips

Give yourself clear definitions of  $A, B, C$ .

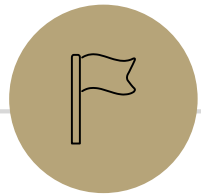
Make a table of all the formulas you need before you start actually calculating.

Calculate "size-by-size" and incorporate into the total.

Basic check: If (in an intermediate step) you ever:

1. Get a negative value
2. Get a value greater than the prior max by adding (after all the single sets)
3. Get a value less than the prior min by subtracting (after all the pairwise intersections)

Then something has gone wrong.



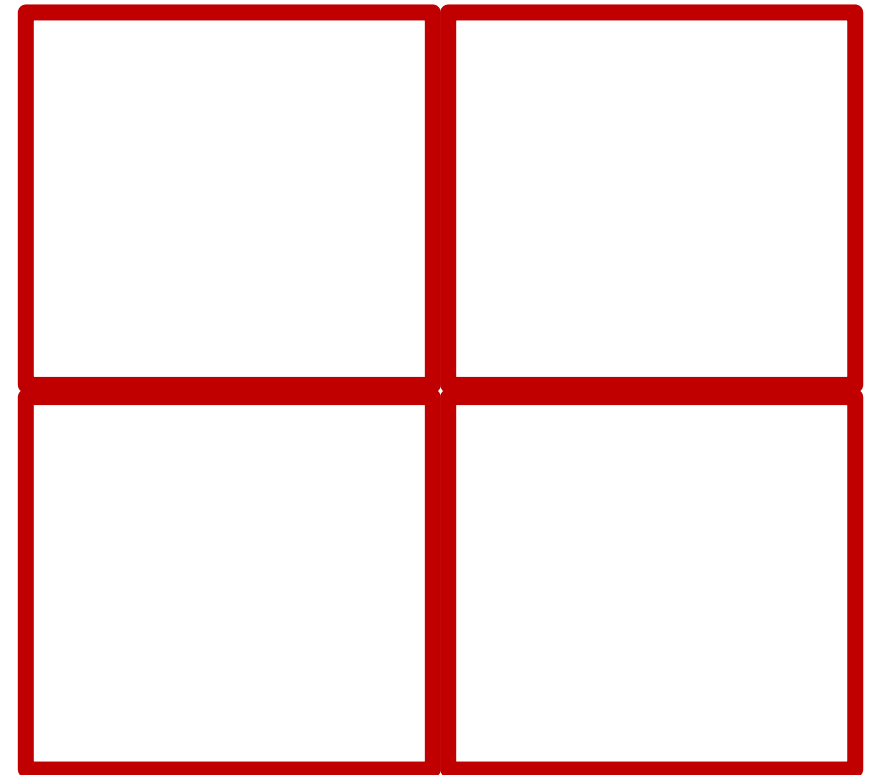
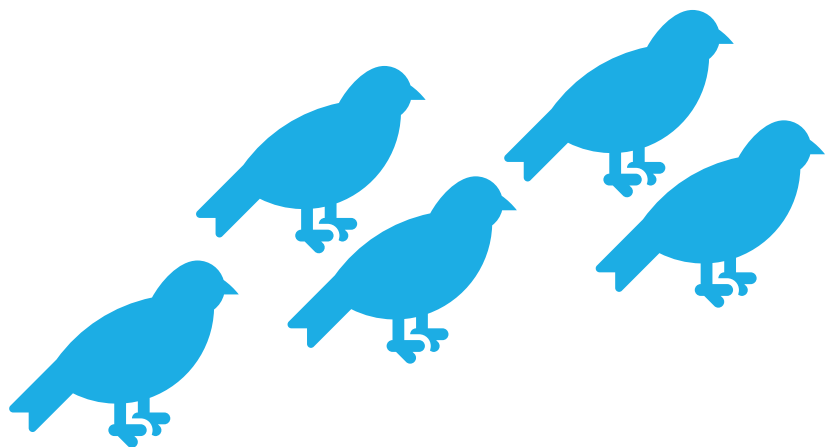
# Pigeonhole Principle

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# Pigeonhole Principle

If you have 5 pigeons, and place them into 4 holes, then...

At least two pigeons are in the same hole.

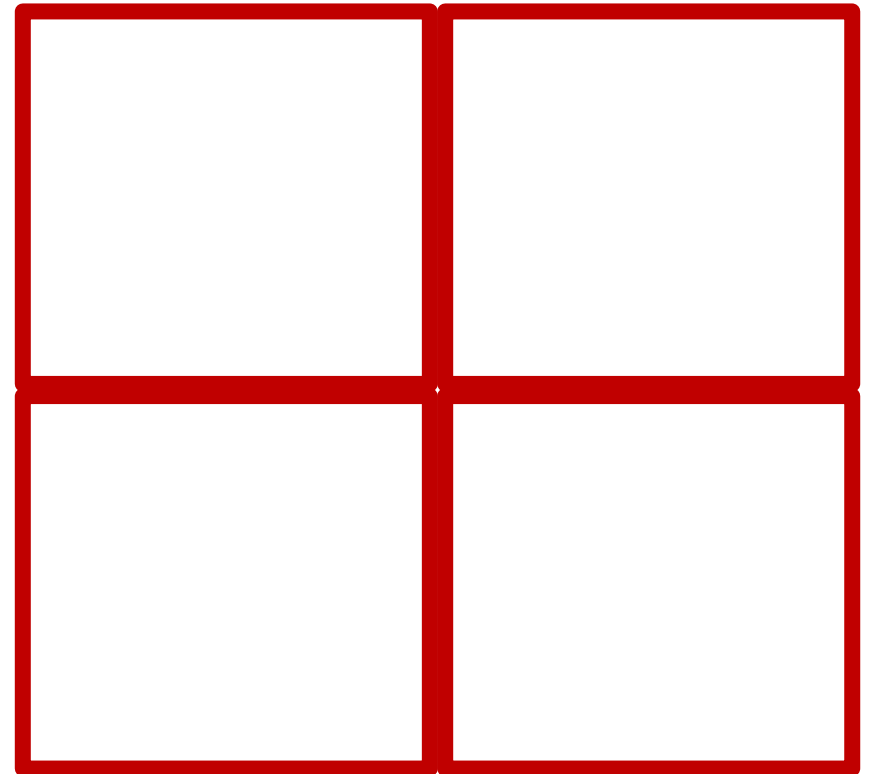
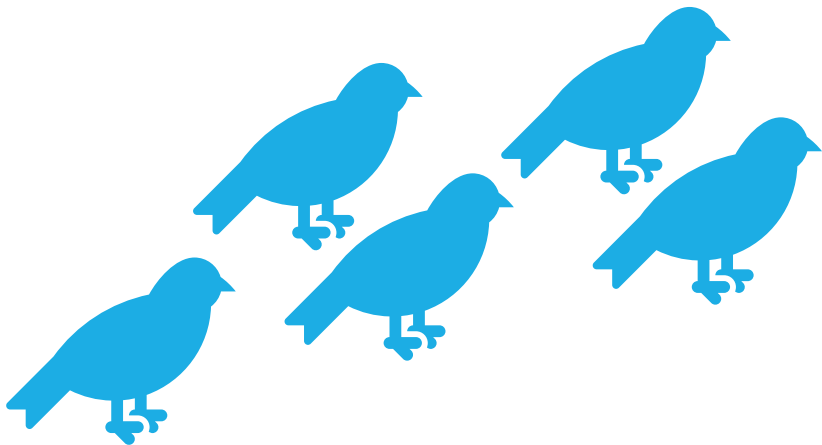


# Pigeonhole Principle

If you have 5 pigeons, and place them into 4 holes, then...

**At least** two pigeons are in the same hole.

It might be more than two.





# Strong Pigeonhole Principle

If you have  $n$  pigeons and  $k$  pigeonholes, then there is at least one pigeonhole that has at least  $\lceil \frac{n}{k} \rceil$  pigeons.

$\lceil a \rceil$  is the "ceiling" of  $a$  (it means always round up,  $\lceil 1.1 \rceil = 2$ ,  $\lceil 1 \rceil = 1$ ).

# An example

If you have to take 10 classes, and have 3 quarters to take them in, then...

Pigeons: The classes to take

Pigeonholes: The quarter

Mapping: Which class you take the quarter in.

Applying the (generalized) pigeonhole principle, there is at least one quarter where you take at least  $\left\lceil \frac{10}{3} \right\rceil = 4$  courses.

# Practical Tips

When the pigeonhole principle is the right tool, it's usually the first thing you'd think of or the absolute last thing you'd think of.

For **really** tricky ones, we'll warn you in advance that it's the right method (you'll see one in the section handout).

When applying the principle, say:

What are the pigeons

What are the pigeonholes

How do you map from pigeons to pigeonholes

Look for – a set you're trying to divide into groups, where collisions would help you somehow.