Discrete Structures for Computer Science

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Lecture #16: Counting Basics

Based on materials developed by Dr. Adam Lee
Today’s Topics

- Introduction to combinatorics
- Product rule
- Sum rule
**What *is* combinatorics?**

**Combinatorics** is the study of arrangements of discrete objects.

*We can think of this as a fancy word for “counting”*

**Many** applications throughout computer science:
- Algorithm complexity analysis
- Resource allocation & scheduling
- Security analysis
- ...

Today, we will learn the basics of counting. More advanced topics will be covered in later lectures.
A motivating example...

To access most computer systems, you need to login with a user name and a password.

Suppose that for a certain system

- Passwords must contain either 6, 7, or 8 characters
- Each character must be an uppercase letter or a digit
- Every password must contain at least one digit

How many valid passwords are there?
Solving these types of problems requires that we learn how to count complex objects.

Fortunately, we can solve many types of combinatorial problems using two simple rules:

- **The product rule**
- **The sum rule**
Product rule applies when a counting problem can be broken into multiple tasks

**The Product Rule:** Suppose a procedure can be broken into a sequence \( t_1, t_2, \ldots, t_k \) of tasks. Further, let there be \( n_1, n_2, \ldots, n_k \) ways to complete each task. Then there are \( n_1 \times n_2 \times \ldots \times n_k \) ways to complete the procedure.

To apply the product rule, do the following:

1. Identify each task \( t_1, \ldots, t_k \)
2. For each task \( t_i \), determine the \( n_i \), the number of possible ways to complete \( t_i \)
3. Compute \( n_1 \times n_2 \times \ldots \times n_k \)

Let’s look at a few examples...
An example: Assigning offices

**Example:** It is Sherif and Bill’s first day of work at Pitt. If there are 10 unused offices in their department, how many ways can Sherif and Bill be assigned an office?

**Step 1:** Determine tasks
1. Give Sherif an office
2. Give Bill an office

**Step 2:** Count possible completions
1. Can give any one of 10 offices to Sherif
2. Can give any one of the remaining 9 offices to Bill

**Step 3:** Compute the product
- Sherif and Bill can be assigned offices in $10 \times 9 = 90$ ways!
Auditorium Seating

**Example:** The chairs in an auditorium are to be labeled using an upper case letter and a positive number not exceeding 100 (e.g., B23). What is the maximum number of seats that can be placed in the auditorium?

**Solution:**
- Task 1: Count the letters that can be used \((26)\)
- Task 2: Count the numbers that can be used \((100)\)
- So, the auditorium can hold \(26 \times 100 = 2600\) chairs.
Example: How many bit strings of length 5 are there?

Solution:

- Task 1: Choose first bit \(2\)
- Task 2: Choose second bit \(2\)
- Task 3: Choose third bit \(2\)
- Task 4: Choose fourth bit \(2\)
- Task 5: Choose fifth bit \(2\)

\[\text{So, there are } 2 \times 2 \times 2 \times 2 \times 2 = 2^5 = 32 \text{ bit strings of length 5}\]
Example: How many 1-to-1 functions are there mapping a set A containing m elements to another set B containing n elements (assuming that m ≤ n)?

Solution:

- Task 1: Map first element of A to B
- Task 2: Map second element of A to B
- Task 3: Map third element of A to B
- ...
- Task m: Map last element of A to B

So, there are a total of \( n \times (n - 1) \times \ldots \times (n - m + 1) \) 1-to-1 functions from A to B.
License Plates

**Example:** Suppose that in some state, license plates consist of three letters followed by three decimal digits. How many valid license plates are there?

**Solution:** There are $26^3 \times 10^3 = 17,576,000$ possible valid license plates.
In-class exercises

Top Hat
The sum rule applies when a single task can be completed using several different approaches.

**The Sum Rule:** Suppose that a single task can be completed in either one of \(n_1\) ways, one of \(n_2\) ways, ..., or one of \(n_k\) ways. Then the task can be completed in \(n_1 + n_2 + \ldots + n_k\) different ways.

**Note:** We can break the set of all possible solutions to the problem into disjoint subsets. E.g., if we have \(k\) “classes” of solutions, then \(S = S_1 \cup S_2 \cup \ldots \cup S_k\)

- \(|S| = |S_1 \cup S_2 \cup \ldots \cup S_k|\)
- \(= |S_1| + |S_2| + \ldots + |S_k|\) \(\text{Since } S_1, \ldots, S_k \text{ are disjoint}\)
- \(= n_1 + n_2 + \ldots + n_k\)
Example: Suppose that either a CS professor or a CS graduate student can be nominated to serve on the CS Day Committee. If there are 21 CS professors and 101 CS graduate students, how many ways can this seat on the committee be chosen?

Solution:

- Let
  - \( P \) be the set of professors
  - \( G \) be the set of graduate students
  - \( S \) be the solution set, with \( S = P \cup G \)

- Then there are \( |S| = |P \cup G| = |P| + |G| = 21 + 101 = 122 \) ways to fill the empty seat on the committee.
Travel Choices

Example: Jane wants to travel from Pittsburgh to New York City. If she flies, she can leave at any one of 12 departure times. If she takes the bus, she can leave at any one of 6 departure times. If she takes the train, she can leave at any one of 4 departure times. How many different departure times can Jane choose from?

Solution:

- $S = F \cup B \cup T$, so
- $|S| = |F \cup B \cup T|$
- $= |F| + |B| + |T|$
- $= 12 + 6 + 4$
- $= 22$ departure times
The product and sum rules are kind of boring...

Most interesting counting problems cannot be solved using the product rule or the sum rule alone...

... but many interesting problems can be solved by combining these two approaches!

Let’s revisit our password example...
Passwords revisited…

To access most computer systems, you need to login with a user name and a password.

Suppose that for a certain system:
- Passwords must contain either 6, 7, or 8 characters
- Each character must be an uppercase letter or a digit
- Every password must contain at least one digit

How many valid passwords are there?

Use the product rule to count passwords of each possible length!

Choices: Sum rule!
First, we’ll apply the sum rule

Let:

- $P_6$ = Set of passwords of length 6
- $P_7$ = Set of passwords of length 7
- $P_8$ = Set of passwords of length 8
- $S = P_6 \cup P_7 \cup P_8$

Note: $|S| = |P_6| + |P_7| + |P_8|$

Since each element of $P_6$, $P_7$, and $P_8$ is made up of independent choices of letters and numbers, we can apply the product rule to determine $|P_6|$, $|P_7|$, and $|P_8|$
Observation: To figure out the number of 6-character passwords containing at least one number, it is easier for us to count all 6-character passwords and then subtract away those passwords not containing a number.

Note: there are

- \((26 + 10)^6 = 36^6\) 6-character passwords
- \(26^6\) 6-character passwords not containing a digit

So, \(|P_6| = 36^6 - 26^6 = 1,867,866,560\)
We can compute

- $|P_6| = 36^6 - 26^6 = 1,867,866,560$
- $|P_7| = 36^7 - 26^7 = 70,332,353,920$
- $|P_8| = 36^8 - 26^8 = 2,612,282,842,880$

By leveraging our earlier observation that $|S| = |P_6| + |P_7| + |P_8|$, we can conclude that there are $2,684,483,063,360$ valid passwords for our target system.
An IP address (in IPv4) is a 32-bit string that is used to identify a computer that is connected to the Internet.

There are three categories of IP addresses that can be assigned to computers:

1. **Class A** addresses consist of the prefix “0” followed by a 7-bit network ID and a 24-bit host ID
2. **Class B** addresses consist of the prefix “10” followed by a 14-bit network ID and a 16-bit host ID
3. **Class C** addresses consist of the prefix “110” followed by a 21-bit network ID and an 8-bit host ID
So how many valid IP addresses are there?

Note: IP addresses are subject to restrictions:
- 1111111 cannot be used as the network ID of a Class A IP
- Host IDs consisting of only 1s or only 0s cannot be used

To count IP addresses, we will use the sum rule and the product rule. So \( S = S_A \cup S_B \cup S_C \), so \(|S| = |S_A| + |S_B| + |S_C|\)

Compute \( S_A \):
- \(2^7 - 1\) network IDs since 1111111 can’t be used
- \(2^{24}\) - 2 host IDs for each network ID
- Total of 2,130,706,178 Class A IP addresses
So how many valid IP addresses are there? (cont.)

Compute $S_B$:
- $2^{14}$ network IDs
- $2^{16} - 2$ host IDs for each network ID
- Total of 1,073,709,056 Class B IP addresses

Compute $S_C$:
- $2^{21}$ network IDs
- $2^8 - 2$ host IDs for each network ID
- Total of 532,676,608 Class C IP addresses

Since $|S| = |S_A| + |S_B| + |S_C|$, there are 3,737,091,842 IP addresses that can be assigned to computers connected to the Internet!
In-class exercises

Top Hat
Final Thoughts

- Combinatorics is just a fancy word for counting!

- There are many uses of combinatorics throughout computer science

- We can solve a variety of interesting problems using simple rules like the product rule and the sum rule

Next time:
- Inclusion/Exclusion principle (Section 6.1)
- The pigeonhole principle (Section 6.2)