https://xkcd.com/1153/
https://www.explainxkcd.com/wiki/index.php/1153:_Proof

Mathematical Foundations

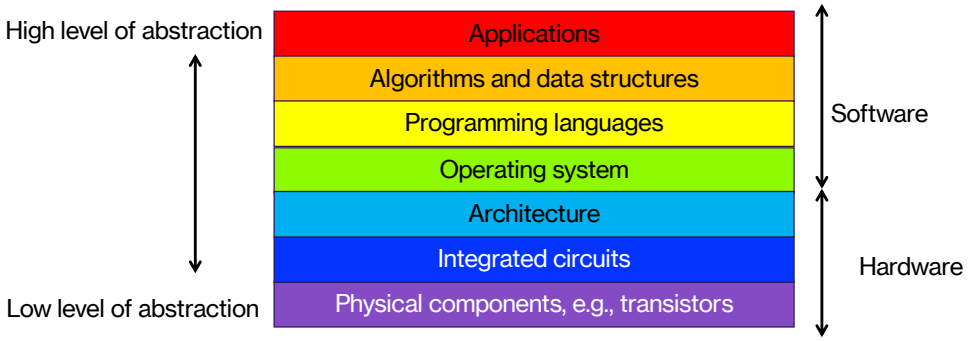
Propositional Logic

CS51 – Spring 2026

Today open's a new chapter in our class, that of mathematical foundations of computer science.

Abstraction

- Critical technique for managing complexity. We will simplify and generalize information by hiding details when they are not important. This allows us to cultivate a higher level of understanding without being overwhelmed with insignificant details.



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Throughout this class, we have talked about the important concept of abstraction which allows us to handle the complexity of modern computer systems. Abstraction looked like a tower, where each layer depends on the previous one. So far, we have focused on the lower half of that tower, mostly on the physical side of computer systems, but we have also seen how they are related to a mathematical side of computer science through their affinity with Boolean Algebra. Today, we will start a new chapter in the course that will allow us to not blindly trust that something works, be it the layers in the tower of abstraction or the functions in the programs we have built, but prove that it will work as intended.

Proofs

- **Proofs** are mathematical techniques that will allow us to demonstrate the truth of a claim, starting with certain assumptions and using logical reasoning to reach the conclusion while leaving no doubt to us or the reader of our proof.
  - For example, the claim might have to do about the correctness or efficiency of an algorithm or circuit we designed to solve a problem.
- Proofs have both practical implications as they reduce bugs and theoretical implications as they give us insights into structural aspects of problems we try to tackle.
- Proofs demonstrate that a statement is true for *all possible cases.* This contrasts "good-enough" experimental approaches where we just try a few cases.

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Proofs are mathematical techniques that will allow us to demonstrate the truth of a claim, starting with certain assumptions and using logical reasoning to reach the conclusion while leaving no doubt to us or the reader of our proof. For example, the claim might have to do about the correctness or efficiency of an algorithm we designed to solve a problem. Proofs have both practical implications as they reduce bugs and theoretical implications as they give us insights into structural aspects of problems we try to tackle.
Proofs demonstrate that a statement is true for *all possible cases*. This contrasts "good-enough" experimental approaches where we can try a few cases and call it a day.

Logic

- We are familiar with the concept of truth and falsity, both through Boolean algebra and working with circuits.
- A lot of what we have been learning falls under **Logic**, the study of truth and falsity, of theorems, and proofs.
- Logic is the foundation of all computer science. It's behind the programs we write and behind the gates we connect to build circuits.
- Many types of logic. We will focus on **propositional logic**.

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So far, we have been working a lot with the concept of truth and falsity, be it through Boolean algebra or circuits. A lot of what we have been learning so far falls under *Logic*, the study of truth and falsity, of theorems and proofs. Logic is the foundation of all computer science. It's behind the if statements or the while loops we write or any program really. It's behind the gates and wires that act as physical manifestation of logical operations we apply on signals that represent information. There are different types of formal logic (we care about the form of the arguments rather than the content). We will focus on propositional logic but if you continue in more advanced CS classes you will encounter more of them, such a predicate logic.

Propositions

- A **proposition** is a statement that is true or not. For example,
  - "CS51 has an enrolment of 47 students."
  - "Pomona College is the founding college of the Claremont Colleges Consortium."
- For a particular proposition p, the **truth value** of p is its truth or falsity. The truth values for those statements are false and true, respectively.
- Propositional logic is the study of propositions, including how to formulate statements as propositions, how to evaluate whether a proposition is true or false, and how to manipulate propositions.

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A *proposition* is a statement that is true or not. For example, the statements "CS51 has an enrolment of 47 students" and "Pomona College is the founding college of the Claremont Colleges Consortium" are both propositions. For a particular proposition p, the truth value of p is its truth or falsity. The truth values for those statements are false and true, respectively. Propositional logic is the study of propositions, including how to formulate statements as propositions, how to evaluate whether a proposition is true or false, and how to manipulate propositions.

Atomic propositions

- An **atomic proposition** is a proposition that is conceptually indivisible. It is also known as a **Boolean variable**. For example:
  - "Pomona College's mascot is Cecil the Sagehen."
- **Practice Time**: Can you come up with an example of an atomic proposition?

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An *atomic proposition* is a proposition that is conceptually indivisible. It is also known as a *Boolean variable*. We cannot break it further. For example, "Pomona College's mascot is Cecil the Sagehen."
Can you come up with your own examples for atomic propositions?

Compound propositions

- A **compound proposition** is a proposition that is built up out of atomic propositions $p_1, p_2, \ldots, p_k$ that are connected with **logical connectives**.
- It is also called a **Boolean expression** or **Boolean function/formula** over $p_1, p_2, \ldots, p_k$. For example:
  - Claremont is a city in Southern California *or* Portland is a city in Southern California.
- **Practice Time**: What logical connectives have we seen so far?

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A *compound proposition* is a proposition that is built up out of k atomic propositions p1, p2, …, pk that are connected with **logical connectives**. It is also called a *Boolean expression* or *Boolean function/formula* over p1, p2, …, pk. For example: "Claremont is a city in Southern California or Portland is a city in Southern California." The two atomic propositions are p1="Claremont is a city in Southern California", p2=Portland is a city in Southern California" and are connected with an the logical connective or. What logical connectives have we seen so far?

Logical connectives we have seen: ¬,∧, ∨,⊕

- **Logical connectives** are the glue that creates the more complicated compound propositions from simpler propositions. We have already seen four:
  - Negation [not, ¬]. The proposition $\neg p$ ("not p," called the negation of the proposition p) is true when the proposition p is false, and is false when p is true.
  - Conjunction [and, ∧]. The proposition $p \wedge q$ ("p and q," the conjunction of the propositions p and q) is true when both propositions p and q are true and is false when one or both of p or q is false.
  - Disjunction [or, ∨]. The proposition $p \vee q$ ("p or q," the disjunction of the propositions p and q) is true when one or both propositions p or q is true and is false when both p and q are false.
  - Exclusive or [xor, ⊕]. The proposition $p \oplus q$ is true when one of p or q is true, but not both. Thus $p \oplus q$ is false when both p and q are true, and when both p and q are false.
- **Practice Time**: Can you come up with an example of compound proposition?

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Logical connectives are the glue that creates the more complicated compound propositions from simpler propositions. We have already seen quite a few:
i) Negation [not, ¬]. The proposition ¬p ("not p," called the negation of the proposition p) is true when the proposition p is false, and is false when p is true.
ii) Conjunction [and, ∧]. The proposition p ∧ q ("p and q," the conjunction of the propositions p and q) is true when both of the propositions p and q are true, and is false when one or both of p or q is false. Be careful to not confuse it with the bitwise xor operation in Python.
iii) Disjunction [or, ∨]. The proposition p ∨ q ("p or q," the disjunction of the propositions p and q) is true when one or both of the propositions p or q is true, and is false when both p and q are false.
iv) Exclusive or [xor, ⊕]. The proposition p ⊕ q is true when one of p or q is true, but not both. Thus p ⊕ q is false when both p and q are true, and when both p and q are false.
Unfortunately, the word "or" in English can mean either inclusive or exclusive or, depending on the context in which it's being used. When you see the word "or," you'll have to think carefully about which meaning is intended.
Can you come up with your own examples for compound propositions?

New logical connective: ⇒

- Implication [if/then, ⇒]. It expresses a familiar idea from everyday life, though one that's not quite captured by a single English word.
- Consider the sentence "If you tell me how much money you make, then I'll tell you how much I make."
- The proposition $p \Rightarrow q$ is true when the truth of p implies the truth of q. In other words, $p \Rightarrow q$ is true unless p is true and q is false.
- In the implication $p \Rightarrow q$, the proposition p is called the *antecedent* or the *hypothesis*, and the proposition q is called the *consequent* or the *conclusion.*
- Implication doesn't mean that p caused q. Only that p being true implies that q is true.
  - Or in other words, p being true lets us conclude that q is true.

p	q	$p \Rightarrow q$
T	T	T
$\boldsymbol{T}$	$\boldsymbol{F}$	$\boldsymbol{F}$
F	T	T
F	F	T

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There are more logical connectives used in propositional logic that we have not seen so far. The first one is implication.
Implication [if/then, ⇒]: It expresses a familiar idea from everyday life, though one that's not quite captured by a single English word. Consider the sentence "If you tell me how much money you make, then I'll tell you how much I make." It's easiest to think of this sentence as a promise: I've promised that I'll tell you my financial situation, as long as you tell me yours. I haven't promised anything about what I'll do if you don't tell me your salary—I can abstain from revealing anything about myself, or I might spontaneously tell you my salary anyway, but the point is that I haven't guaranteed anything. (But you'd justifiably call me a liar if you told me what you make, and I failed to disclose my salary in return.) This kind of promise is expressed as an implication in propositional logic.
The proposition p ⇒ q is true when the truth of p implies the truth of q. In other words, p ⇒ q is true unless p is true and q is false.
In the implication p ⇒ q, the proposition p is called the *antecedent* or the *hypothesis*, and the proposition q is called the *consequent* or the *conclusion*. A confusing aspect is that implication doesn't mean that p caused q. Only that p being true implies that q is true. Or in other words, p being true lets us conclude that q is true

Practice Time: truth values of implications

- What will the following propositions evaluate to?
  - 1 + 1 = 2 implies that 2 + 3 = 5.
  - 2 + 3 = 4 implies that 2 + 2 = 4.
  - 2 + 2 = 4 implies that 2 + 1 = 5.
  - 2 + 3 = 4 implies that 2 + 3 = 6.

p	q	$p \Rightarrow q$
T	T	T
T	F	F
F	T	T
F	F	T

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Let's practice, what will the following propositions evaluate to? Here's the implication truth table for your convenience.

Answer: truth values of implications

- What will the following propositions evaluate to?
  - 1 + 1 = 2 implies that 2 + 3 = 5. (“True implies True” is true.)
  - 2 + 3 = 4 implies that 2 + 2 = 4. (“False implies True” is true.)
  - 2 + 2 = 4 implies that 2 + 1 = 5. (“True implies False” is false.)
    - This is false because 2 + 2 = 4 is true, but 2 + 1 = 5 is false.
  - 2 + 3 = 4 implies that 2 + 3 = 6. (“False implies False” is true.)

p	q	$p \Rightarrow q$
T	T	T
T	F	F
F	T	T
F	F	T

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Here are some examples of implications and their truth value:
The following propositions are all true:

1 + 1 = 2 implies that 2 + 3 = 5. (“True implies True” is true.)
2 + 3 = 4 implies that 2 + 2 = 4. (“False implies True” is true.)
2 + 3 = 4 implies that 2 + 3 = 6. (“False implies False” is true.)

But the following proposition is false:

2 + 2 = 4 implies that 2 + 1 = 5. (“True implies False” is false.)
This last proposition is false because 2 + 2 = 4 is true, but 2 + 1 = 5 is false.

New logical connective: ⇔

- If and only if [⇔]: The proposition $p \Leftrightarrow q$ ("p if and only if q") is true when the propositions p or q have the same truth value (both p and q are true, or both p and q are false), and false otherwise.
- The reason that ⇔ is read as "if and only if" is that $p \Leftrightarrow q$ means the same thing as the compound proposition $(p \Rightarrow q) \wedge (q \Rightarrow p)$.

p	q	$p \Leftrightarrow q$	$p \Rightarrow q$	$q \Rightarrow p$	$(p \Rightarrow q) \wedge (q \Rightarrow p)$
T	T	T	T	T	T
T	F	F	F	T	F
F	T	F	T	F	F
F	F	T	T	T	T

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The final logic connect we will see is if and only if [⇔]: The proposition p ⇔ q ("p if and only if q") is true when the propositions p or q have the same truth value (both p and q are true, or both p and q are false), and false otherwise. The reason that ⇔ is read as "if and only if" is that p ⇔ q means the same thing as the compound proposition (p ⇒ q) ∧ (q ⇒ p).
Unfortunately, just like with "or," the word "if" is ambiguous in English. Sometimes "if" is used to express an implication, and sometimes it's used to express an if-and-only-if definition. When you see the word "if" in a sentence, you'll need to think carefully about whether it means ⇒ or ⇔.

Practice Time: truth values of if and only if

- What will the following propositions evaluate to?
  - 1 + 1 = 2 if and only if 2 + 3 = 5.
  - 2 + 3 = 4 if and only if 2 + 2 = 4.
  - 2 + 2 = 4 if and only if 2 + 1 = 5.
  - 2 + 3 = 4 if and only if 2 + 3 = 6.

p	q	$p \Leftrightarrow q$
T	T	T
T	F	F
F	T	F
F	F	T

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Let's practice, what will the following propositions evaluate to? Here's the if and only if truth table for your convenience.

Answer: truth values of if and only if

- What will the following propositions evaluate to?
  - 1 + 1 = 2 if and only if 2 + 3 = 5. ("True if and only if True" is true)
  - 2 + 3 = 4 if and only if 2 + 2 = 4. ("False if and only if True" is false)
  - 2 + 2 = 4 if and only if 2 + 1 = 5. ("True if and only if False" is false)
  - 2 + 3 = 4 if and only if 2 + 3 = 6. ("False if and only if False" is true)

p	q	$p \Leftrightarrow q$
T	T	T
T	F	F
F	T	F
F	F	T

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Did you get these?

Precedence of logical connectives

- The **precedence** of our logical connectives is:
  - negation (¬) has the highest precedence;
  - then there is a three-way tie among ∧, ∨, and ⊕;
  - then there's ⇒;
  - then finally ⇔ has the lowest precedence.

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The precedence (which one is more important and applied first in a Boolean expression) of our logical connectives: negation (¬) has the highest precedence; then there is a three-way tie among ∧, ∨, and ⊕; then there's ⇒; then finally ⇔ has the lowest precedence.

Truth tables for basic logical connectives

p	$\neg p$
T	F
F	T

p	q	$p \wedge q$	$p \vee q$	$p \oplus q$	$p \Rightarrow q$	$p \Leftrightarrow q$
T	T	T	T	F	T	T
T	F	F	T	T	F	F
F	T	F	T	T	T	F
F	F	F	F	F	T	T

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To summarize, here are the truth tables for the logical connectives we have seen.

Practice Time: Compound propositions

- We can now build truth tables for more complex propositions. For example, what is the truth table for $p \wedge q \Rightarrow \neg q$?

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For more complicated propositions, we can fill in a truth table by repeatedly applying the basic truth tables and following the precedence of logical connectives. What is the truth table for this complex proposition?

Practice Time: Complex propositions

- We can now build truth tables for more complex propositions. For example, what is the truth table for $p \wedge q \Rightarrow \neg q$?

p	q	$p \wedge q$	$\neg q$	$p \wedge q \Rightarrow \neg q$
T	T	T	F	F
T	F	F	T	T
F	T	F	F	T
F	F	F	T	T

- The given proposition is true precisely when at least one of p and q is false.

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We can find the truth table for p ∧ q ⇒ ¬q which leads to the conclusion that the given proposition is true precisely when at least one of p and q is false.

Practice time

- Cecil Sagehen, who is 47 years old, was asked at the doctor's office: "If you are over 55 years old, do you have an advance care directive?"
- What should Cecil answer?
- *Hint*: translate this English statement to propositional logic

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Here's a situation where propositional logic can be useful. Let's assume that Cecil Sagehen, who is 47 y.o., goes to the doctor and is asked " "If you are over 55 years old, do you have an advance care directive?" What should Cecil answer?

Answer

- p = "over 55 years old"
- q = "have an advance care directive"
- p ⇒ q is true whenever p is false, and p=“over 55 years old” is false. (That is, False ⇒ anything is true.)
- Thus, Ceil should answer “yes”

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Cecil should say yes. The question is framed as a p implies q proposition. Since p is false, then it doesn't matter whether Cecil has an advance care directive. The statement is true. Sometimes the hardest part is knowing how to translate English to the right propositions.

Practice time: More compound propositions

- What are the truth tables for the following compound propositions?
  - $[p \wedge (p \Rightarrow q)] \Rightarrow q$
  - $[\neg q \wedge (p \Rightarrow q)] \Rightarrow \neg p$

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Let's practice some more with building truth tables. Can you work the following compound propositions?

Answer: More compound propositions

p	q	$\neg p$	$\neg q$	$p \Rightarrow q$	$p \wedge (p \Rightarrow q)$	$[\boldsymbol{p} \wedge (\boldsymbol{p} \Rightarrow \boldsymbol{q})] \Rightarrow \boldsymbol{q}$	$\neg q \wedge (p \Rightarrow q)$	$[\neg \boldsymbol{q} \wedge (\boldsymbol{p} \Rightarrow \boldsymbol{q})] \Rightarrow \neg \boldsymbol{p}$
T	T	F	F	T	T	$\boldsymbol{T}$	F	$\boldsymbol{T}$
T	F	F	T	F	F	$\boldsymbol{T}$	F	$\boldsymbol{T}$
F	T	T	F	T	F	$\boldsymbol{T}$	F	$\boldsymbol{T}$
F	F	T	T	T	F	$\boldsymbol{T}$	T	$\boldsymbol{T}$

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Do you notice that they all evaluate to True?

Tautologies

- A proposition is a **tautology** if it is true under *every* truth assignment.
- For example, if we had a compound proposition over the propositions p and q, it would be a tautology because it is true under all possible assignments for p and q.

p	q	compound proposition
T	T	T
T	F	T
F	T	T
F	F	T

- One reason that tautologies are important is that we can use them to reason about logical statements, which can be particularly valuable when we're trying to prove a claim.

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The Boolean expressions we just saw are called tautologies. A proposition is a tautology if it is true under *every* truth assignment. One reason that tautologies are important is that we can use them to reason about logical statements, which can be particularly valuable when we're trying to prove a claim.

Revisiting practice time – Rules of inference

- ***Modus ponens***: $[p \wedge (p \Rightarrow q)] \Rightarrow q$. If we know both that (a) p is true and that (b) the truth of p implies the truth of q, then we can conclude that q is true.
  - Example:
    - Cecil is a Sagehen.
    - If Cecil is a Sagehen, then Cecil is a grouse.
    - Therefore, Cecil is a grouse.
- ***Modus tolens***: $[\neg q \wedge (p \Rightarrow q)] \Rightarrow \neg p$. If we know both that (a) q is false and that (b) the truth of p implies the truth of q, then we can conclude that p is false.
  - Example:
    - Cecil is not cuddly.
    - If Cecil is a cow, then Cecil is cuddly.
    - Therefore, Cecil is not a cow.
- **Practice Time:** Can you come up with examples for both?

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The exercise we just did showed both compound propositions were tautologies. These three tautologies are so important in Propositional Logic they have their own special names. The first is called modus ponens and the second modus tolens and they are part of rules of inference that can be used to derive conclusions.

Practice time

- What is the truth tables for the following compound proposition?
- $(p \Leftrightarrow q) \wedge (p \oplus q)$

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Let's continue with practicing with this compound proposition.

Answer

- What is the truth tables for the following compound proposition?
- $(p \Leftrightarrow q) \wedge (p \oplus q)$

p	q	$p \Leftrightarrow q$	$p \oplus q$	$(p \Leftrightarrow q) \wedge (p \oplus q)$
T	T	T	F	**F**
T	F	F	T	**F**
F	T	F	T	**F**
F	F	T	F	**F**

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Did you notice that every row evaluates to False?

Satisfiable propositions

- A proposition is **satisfiable** if it is true under *at least one* truth assignment.
- A proposition is **unsatisfiable** if it is not satisfiable.
- That means, the proposition $(p \Leftrightarrow q) \wedge (p \oplus q)$ is unsatisfiable.

p	q	$p \Leftrightarrow q$	$p \oplus q$	$(p \Leftrightarrow q) \wedge (p \oplus q)$
T	T	T	F	$\boldsymbol{F}$
T	F	F	T	$\boldsymbol{F}$
F	T	F	T	$\boldsymbol{F}$
F	F	T	F	$\boldsymbol{F}$

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This brings us to two definitions.
A proposition is **satisfiable** if it is true under at least one truth assignment.
A proposition is **unsatisfiable** if it is not satisfiable. That is, it is false under every single truth assignment
That means, the proposition $(p \Leftrightarrow q) \wedge (p \oplus q)$ we just saw is unsatisfiable as there is no truth assignment.

Practice time: Satisfiable or not?

- Is the proposition $p \vee q \Rightarrow \neg p \wedge \neg q$ satisfiable?

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Can you show using truth tables whether the proposition p ∨ q ⇒ ¬p ∧ ¬q is satisfiable?

Practice time: Satisfiable or not?

- Is the proposition $p \vee q \Rightarrow \neg p \wedge \neg q$ satisfiable?
  - *Yes, it is.*

p	q	$p \vee q$	$\neg p$	$\neg q$	$\neg p \wedge \neg q$	$p \vee q \Rightarrow \neg p \wedge \neg q$
T	T	T	F	F	F	F
T	F	T	F	T	F	F
F	T	T	T	F	F	F
F	F	F	T	T	T	T

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Yes it is satisfiable. We constructed its truth table and we see that we have one truth assignment (p=F, q=F) where the proposition is true.

Complexity theory

- Complexity theory is the subfield of computer science devoted to understanding the computational resources (e.g., time and memory) necessary to solve particular problems.
- One of the central problems is the SAT problem (Boolean Satisfiability problem): you are given a proposition ϕ over n variables and asked to determine whether ϕ is satisfiable.
- The problem is pretty simple to solve. For example, you construct the truth table for the proposition and then check whether there are any True rows in the ϕ's column.
- But this algorithm is not very fast because the truth table has 2^n rows. Even a small n means that this algorithm will not terminate in our lifetime. E.g., for 2^{300} we would exceed the number of particles in the known universe!
- So although there is an algorithm that solves the SAT problem, it is unclear whether there is a substantially more efficient algorithm to solve it.

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Satisfiability plays a prominent role in the field of complexity theory. Complexity theory is the subfield of computer science devoted to understanding the computational resources (primarily time and memory) necessary to solve particular problems. One of the central problems is the SAT problem (Boolean Satisfiability problem): you are given a proposition ϕ over n variables and asked to determine whether ϕ is satisfiable. The problem could be easily solved with what we know so far. We can construct the truth table for the proposition and then check whether for all possible truth assignments for the n variables there are any True rows in the ϕ's column.
But this algorithm is not very fast because the truth table has 2^n rows. Even a small n means that this algorithm will not terminate in our lifetime. E.g., for 2^{300} we would exceed the number of particles in the known universe!
So although there is an algorithm that solves the SAT problem, it is unclear whether there is a substantially more efficient algorithm to solve it.

Satisfiability and a million dollars prize

- This problem is so big that the Clay Mathematics Institute included it in the seven Millennium Prize Problems and will give a $1 million prize to anyone who solves it.
- Why do we care so much about this problem?
- SAT is just as hard as many other computational problems that belong in the class of NP. For NP problems(non-deterministic polynomial time), it is easy to **verify** the correct answer (the correct answer can be verified in polynomial time).
- The question is whether these problems can also be **solved** in polynomial time. This class of problems is known as P.
- That is, we do not know whether P=NP.
- It is widely believed that P≠NP. Solving this problem would have profound implications on fields like cryptography.

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The SAT problem is so big that the Clay Mathematics Institute included it in the seven Millennium Prize Problems and will give a $1 million prize to anyone who solves it. But why do we care so much about this problem?
SAT is just as hard as many other computational problems that belong in the class of NP. For NP problems(non-deterministic polynomial time), it is easy to **verify** the correct answer (the correct answer can be verified in polynomial time) e.g., for SAT, if you give me the truth assignment under which ϕ is satisfiable, I just have to go and plug in these truth assignments to ϕ and confirm that indeed I got back a True.
The question is whether these problems can also be **solved** in polynomial time. This class of problems that can be solved in polynomial time is known as P.
It is widely believed that P≠NP. Solving this problem would have profound implications on fields like cryptography.

Complexity theory pioneers

- **Cook-Levin Theorem**: If you can solve SAT efficiently, then you can solve any problem in NP efficiently.
- Karp also contributed to theory of NP-completeness and along with Lipton showed a relationship between SAT and circuits that have a polynomial number of logic gates

Stephen Cook

Leonid Levin

Richard Karp

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The bulk of these major problems in theoretical computer science was formulated in late 70s and 80s although it is still an active research area. Complexity theory pioneers like Stephen Cook and Leonid Levin gave us the famous Cook-Levin Theorem that roughly says if you can solve SAT efficiently, then you can solve any problem in NP efficiently. Richard Karp, another seminal figure in theoretical computer science, also worked in N—completeness and along with Richard Lipton examined the relationship of SAT with circuits that can have polynomial number of gates. Cook and Karp hold Turing awards.
If you enjoyed this small introduction to complexity theory, make sure you continue with upper division classes like CS140 (Algorithms) and CS101 (Theory and Programming Languages).

Tautology and satisfiability

- Let φ be any proposition. Then φ is a tautology exactly when $\neg\varphi$ is unsatisfiable.
- φ is a tautology when the truth table for φ is all trues, which happens exactly when the truth table for $\neg\varphi$ is all falses. And that's precisely the definition of $\neg\varphi$ being unsatisfiable!

φ	$\neg\varphi$
T	F
T	F
T	F
T	F

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It may be helpful to think about the general relationship between tautology and satisfiability. Let ϕ be any proposition. (We occasionally denote generic propositions by lowercase Greek letters, particularly ϕ ["phi"] or ψ ["psi"].) Then ϕ is a tautology exactly when ¬ϕ is unsatisfiable: ϕ is a tautology when the truth table for ϕ is all "T"s, which happens exactly when the truth table for ¬ϕ is all "F"s. And that's precisely the definition of ¬ϕ being unsatisfiable!

Practice Time

- What are the truth tables for the following compound propositions?
- $\neg(p \wedge q)$
- $(p \wedge q) \Rightarrow \neg q$

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More practice time. Can you fill in the assignments for the truth tables for these two propositions?

Practice Time

- What are the truth tables for the following compound propositions?
- $\neg(p \wedge q)$
- $(p \wedge q) \Rightarrow \neg q$

p	q	$p \wedge q$	$\neg q$	$\neg(\boldsymbol{p} \wedge \boldsymbol{q})$	$(p \wedge q) \Rightarrow \neg q$
T	T	T	F	$\boldsymbol{F}$	$\boldsymbol{F}$
T	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$
F	T	F	F	$\boldsymbol{T}$	$\boldsymbol{T}$
F	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$

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You should have gotten this. Do you notice that they both resulted to identical truth tables.

Logical equivalence

- Two propositions φ and ψ are logically equivalent, written $\varphi \equiv \psi$, if they have exactly identical truth tables (in other words, their truth values are the same under every truth assignment).

p	q	$p \wedge q$	$\neg q$	$\neg(p \wedge q)$	$(p \wedge q) \Rightarrow \neg q$
T	T	T	F	$\boldsymbol{F}$	$\boldsymbol{F}$
T	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$
F	T	F	F	$\boldsymbol{T}$	$\boldsymbol{T}$
F	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$

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Two propositions ϕ and ψ are logically equivalent, written ϕ ≡ ψ, if they have exactly identical truth tables (in other words, their truth values are the same under every truth assignment).

Logical equivalence and tautologies

- To state it differently: φ and ψ are logically equivalent whenever $\varphi \Leftrightarrow \psi$ is a tautology.
- For example, $\neg(p \wedge q)$ and $(p \wedge q) \Rightarrow \neg q$ are logically equivalent:

p	q	$p \wedge q$	$\neg q$	$\neg(\boldsymbol{p \wedge q})$	$(p \wedge q) \Rightarrow \neg q$	$(\neg(\boldsymbol{p \wedge q})) \Leftrightarrow (p \wedge q) \Rightarrow \neg q$
T	T	T	F	$\boldsymbol{F}$	$\boldsymbol{F}$	$\boldsymbol{T}$
T	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$	$\boldsymbol{T}$
F	T	F	F	$\boldsymbol{T}$	$\boldsymbol{T}$	$\boldsymbol{T}$
F	F	F	T	$\boldsymbol{T}$	$\boldsymbol{T}$	$\boldsymbol{T}$

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To state it differently: two propositions ϕ and ψ are logically equivalent whenever $\phi \Leftrightarrow \psi$ is a tautology.
$\neg(p \wedge q)$ and $(p \wedge q) \Rightarrow \neg q$ are logically equivalent as it can be seen in the truth table

Important laws of logic

- **Law of identity**. $p \wedge T \equiv p$ and $p \vee F \equiv p$: for any proposition p, p is identical to itself.
- **Law of the excluded middle**. $p \vee \neg p$: for any proposition p, either p is true or p is false; there is nothing "in-between" true and false. This is a tautology.
- **Law of non-contradiction**.$\neg(p \wedge \neg p)$: for any proposition p, p and its contradiction/negation, $\neg p$, cannot both be simultaneously true. This is a tautology.

p	q	$\neg p$	$\neg q$	$p \wedge T \equiv p$	$p \vee F \equiv p$	$p \vee \neg p$	$\neg(p \wedge \neg p)$
T	T	F	F	***T***	***T***	***T***	***T***
T	F	F	T	***T***	***T***	***T***	***T***
F	T	T	F	***F***	***F***	***T***	***T***
F	F	T	T	***F***	***F***	***T***	***T***

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The exercise we just did showed both compound propositions were tautologies. These three tautologies are so important in Propositional Logic they have their own special names. The first is called modus ponens and the second modus tolens and they are part of rules of inference that can be used to derive conclusions.

Literals, CNFs, and DNFs

- A **literal** is a Boolean variable (a.k.a. an atomic proposition) or the negation of a Boolean variable.
  - This means that both p and $\neg p$ are literals.
- A proposition is in conjunctive normal form (CNF) if it is the conjunction of one or more clauses, where each clause is the disjunction of one or more literals.
- A proposition is in disjunctive normal form (DNF) if it is the disjunction of one or more clauses, where each clause is the conjunction of one or more literals.
- Less formally, a proposition in conjunctive normal form is "the and of a bunch of ors," and a proposition in disjunctive normal form is "the or of a bunch of ands."

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Less formally, a proposition in conjunctive normal form is "the and of a bunch of ors," and a proposition in disjunctive normal form is "the or of a bunch of ands."

A somewhat familiar theorem

- *Theorem*: For any proposition φ, there is a proposition ψ_{dnf} over the same Boolean variables and in disjunctive normal form such that $\varphi \equiv \psi_{dnf}$.

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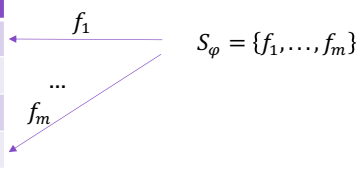
We have already worked with CNFs so it shouldn't come as a surprise if you see this theorem. We just formalize things now using propositional logic.
Theorem: For any proposition φ, there is a proposition ψ_{dnf} over the same Boolean variables and in disjunctive normal form such that $\varphi \equiv \psi_{dnf}$.
Theorem 2: All propositions are expressible in CNF. For any proposition ϕ, there is a proposition φ_{cnf} over the same Boolean variables and in conjunctive normal form such that $\varphi \equiv \varphi_{cnf}$.

Proof of Theorem

- Let φ be an arbitrary proposition, say over the Boolean variables $p_1, \ldots, p_k$.
- Build the truth table for φ, and let $S_\varphi = \{f_1, f_2, \ldots, f_m\}$ denote the set of m truth assignments for $p_1, \ldots, p_k$ under which φ is true.

p_1	p_2	...	p_k	φ
T	F	...	F	T
T	F	...	T	F
...	...	...	...	...
F	F	...	T	T



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Let φ be an arbitrary proposition, say over the Boolean variables $p_1, \ldots, p_k$. We start by building the truth table for φ, and let $S_\varphi = \{f_1, f_2, \ldots, f_m\}$ denote the set of m truth assignments for $p_1, \ldots, p_k$ under which φ is true (that is, we isolate the rows that ϕ is true, as we have already done in the past.)

For example, in this truth table, we see that we have k variables and rows 1, potentially some intermediates, and the last row. That gives us the set of m truth assignments.

Proof of Theorem

- Looking at the truth table of φ, for any particular assignment f_i for the variables $p_1, \ldots, p_k$ that makes φ true, we'll construct a conjunction c_{f_i} that's true under f_i and false under all other assignments that makes φ true.
  - Let $x_1, x_2, \ldots, x_l$ be the variables assigned true by f_i, and $y_1, y_2, \ldots, y_{k-l}$ be the variables assigned false by f_i. Then the clause:
  - $c_{f_i} = x_1 \wedge x_2 \wedge \ldots \wedge x_\ell \wedge \neg y_1 \wedge \neg y_2 \wedge \ldots \wedge \neg y_{k-l}$ is true under f_i, and c_{f_i} is false under every other truth assignment.

p_1	p_2	...	p_k	φ
T	***F***	...	***F***	***T***
T	F	...	T	F
...	...	...	...	...
F	F	...	T	T

$c_{f_1} = p_1 \wedge \neg p_2 \wedge \cdots \wedge \neg p_k$

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Looking at the truth table of φ, for any particular assignment f_i for the variables $p_1, \ldots, p_k$ that makes φ true, we'll construct a conjunction c_{f_i} that's true under f_i and false under all other assignments that makes φ true.

Let $x_1, x_2, \ldots, x_l$ be the variables assigned true by f_i, and $y_1, y_2, \ldots, y_{k-l}$ be the variables assigned false by f_i. Then the clause:

$c_{f_i} = x_1 \wedge x_2 \wedge \ldots \wedge x_\ell \wedge \neg y_1 \wedge \neg y_2 \wedge \ldots \wedge \neg y_{k-l}$ is true under f_i, and c_{f_i} is false under every other truth assignment.

For example, c_f_1 would be the conjunction of p1 and not p2 … and not pk. We would repeat this process for all m assignments that result to ϕ being true,

Proof of Theorem

- We will repeat this process for all truth assignments that make φ true, e.g.,

p_1	p_2	...	p_k	φ
T	F	...	F	T
T	F	...	T	F
...	...	...	...	...
$\boldsymbol{F}$	$\boldsymbol{F}$	...	$\boldsymbol{T}$	$\boldsymbol{T}$

$$c_{f_m} = \neg p_1 \wedge \neg p_2 \wedge \cdots \wedge p_k$$

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We will repeat this process for all truth assignments that make φ true, e.g., here we will do it for the last row.

Proof of Theorem

- We can now construct a DNF proposition ψ_{dnf} that is logically equivalent to φ by "or"ing together the clause c_{f_i} for each truth assignment f_i, i = 1, …, m, $m \geq 1$ that makes φ true.
- Define $\psi_{dnf} = c_{f_1} \vee c_{f_2} \vee \ldots \vee c_{f_m}$ (*)

p_1	p_2	…	p_k	φ	ψ_{dnf}
T	***F***	…	***F***	***T***	***T***
T	*F*	…	*T*	*F*	*F*
…	…	…	…	…	…
F	***F***	…	***T***	***T***	***T***

$\psi_{dnf} = c_{f_1} \vee \cdots \vee c_{f_m}$

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Putting all them together, can now construct a DNF proposition ψ_{dnf} that is logically equivalent to φ by "or"ing together the clause c_{f_i} for each truth assignment f_i, i = 1, …, m, $m \geq 1$ that makes φ true.
Define $\psi_{dnf} = c_{f_1} \vee c_{f_2} \vee \ldots \vee c_{f_m}$ (*)

Proof of Theorem

- Then ψ_{dnf} is true under every truth assignment f_i under which φ was true (because the clause c_{f_i} is true under f_i).
- And, for a truth assignment f under which φ was false, every disjunct in ψ_{dnf} evaluates to false, so the entire disjunction is false under such an f, too.
- Thus, $\varphi \equiv \psi_{dnf}$
- Are we done?

p_1	p_2	...	p_k	φ	ψ_{dnf}
T	F	...	F	***T***	***T***
T	F	...	T	***F***	***F***
...	...	...	...	...	...
F	F	...	T	***T***	***T***

$\psi_{dnf} = c_{f_1} \vee \cdots \vee c_{f_m}$

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Then ψ_{dnf} is true under every truth assignment f_i under which φ was true (because the clause c_{f_i} is true under f_i).
And, for a truth assignment f under which φ was false, every disjunct in ψ_{dnf} evaluates to false, so the entire disjunction is false under such an f, too.
Thus, $\varphi \equiv \psi_{dnf}$
Are we done?

$\psi_{dnf} = c_{f_1} \vee c_{f_2} \vee \ldots \vee c_{f_m}$ (*)

Proof of Theorem

- There's one thing we have to be careful about: what happens if S_φ is an empty set, that is if φ is unsatisfiable?
- The construction in $(*)$ doesn't work, but it's easy to handle this case separately: we simply choose an unsatisfiable DNF proposition like the opposite of the law of non-contradiction, i.e. $p \wedge \neg p$ as ψ_{dnf}.

p_1	p_2	...	p_k	φ	ψ_{dnf}
T	F	...	F	F	F
T	F	...	T	F	F
...	...	...	...	...	...
F	F	...	T	F	F

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There's one thing we have to be careful about: what happens if S_φ is an empty set, that is if φ is unsatisfiable?
The construction in $(*)$ doesn't work, but it's easy to handle this case separately: we simply choose an unsatisfiable DNF proposition like $p \wedge \neg p$ as ψ_{dnf}.

Proofs in computer science

- The type of proof we saw is known as **proof by cases**, with two cases corresponding to φ being satisfiable and φ being unsatisfiable being proven separately.
- There are many types of proofs used in computer science.
  - Together, we will see loop invariant proofs and proofs by induction but if you continue with more advanced computer science courses you will encounter even more.
- There's genuine creativity in producing proofs along with key strategies that one can learn.

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The type of proof we saw for is known as **proof by cases**, with two cases corresponding to φ being satisfiable and φ being unsatisfiable being proven separately.
There are many types of proofs used in computer science. Together, we will see loop invariant proofs and proofs by induction but if you continue with more advanced computer science courses, like CS54, CS140, and theory electives, you will encounter even more.
it's worth emphasizing again that there's genuine creativity required in proving these theorems. By learning more proof techniques and through practice, you can get better at having the kinds of creative ideas that lead to proofs—but that doesn't mean that these results should have been "obvious" to you in advance.