

Lecture 1 - 5th Sept 2024

Formal Verification (FV): viewing a program as a logical argument and determining whether it behaves correctly using symbolic reasoning.

What is logical reasoning?

- Premises: facts
- Conclusions: what we deduce from the premises. The conclusion logically follows from the facts.
 - ↳ Example: if the train arrives late and there are no taxis at the station, then John is late for his meeting. John is not late for his meeting. The train did arrive late. Were there taxis at the station?
 - ↳ Yes!

What is formal logic?

- Syntax: acceptable sentence in the logic
- Semantics: what the symbols and sentences in the logic mean.
- proof theory: how the valid proofs in the logic are constructed.
- Logic provides:
 - ↳ A language for expressing knowledge precisely (modelling / specification)
 - ↳ A way to reason about the consequences of that knowledge rigorously (proof / verification)
- A logic is formal if there is only one possible interpretation of a formula in the language.

- formal logic is concerned with the structure of the argument.
- we use symbols in the syntax to represent phrases in the sentences. It's also called symbolic logic.
 - ↳ using symbols allows us to conquer complexity and eliminate non-logical aspects of argument.
- Propositional logic: a declarative sentence that is either true or false, but not both.
- Predicate logic: a means of describing relationships between objects, and a quantification over objects.
 - ↳ eg: "every course has an instructor."
- Specification: ways of describing what a system is required to do.
- program correctness: a program is correct iff the output is correct for every input.
- the syntax of a logic defines how to arrange symbols into a well-formed formula (wff)

Semantics:

- \models : logical implication
 - \Leftrightarrow : logical equivalence
 - \vdash : proves $\rightarrow P_1, P_2, \dots, P_n \vdash Q$ means that from P_1, P_2, \dots, P_n , we can prove Q using a proof theory.
- ↗ NOT a part of wff, but a meta-level symbol.

Proof Theories: methods that perform mechanical manipulations on strings of symbols.

↳ based on pattern matching!

On $P_1, P_2, \dots, P_n \vdash Q$ and $P_1, P_2, \dots, P_n \models Q$,

goals: if we aren't yet sure they are valid / proven

theorems: if they've been determined to be valid / proven

Soundness: a proof theory is sound if whenever

$P_1, P_2, \dots, P_n \vdash Q$ (we have a proof), then

$P_1, P_2, \dots, P_n \models Q$ (valid)

Completeness: a proof theory is complete if

whenever $P_1, P_2, \dots, P_n \models Q$ (valid) then $P_1, P_2, \dots, P_n \vdash Q$ (there is a proof).

Propositional Connectives:

symbol	informal meaning	george
\neg	negation (not)	!
\wedge	conjunction (and / both)	&
\vee	disjunction (or / at least one)	
\Rightarrow	implication (if / implies)	=>
\Leftrightarrow	equivalent (biconditional, iff)	<=>

Brackets and Precedence:

- Brackets around the outermost formula are usually omitted.

- The order of precedence for the operators is shown in the above table, with \neg having the highest precedence and \Leftrightarrow having the lowest.
- All binary logical connectives are right-associative.
 - Eg: $a \vee b \vee c \rightarrow a \vee (b \vee c)$
 - $a \Rightarrow b \Rightarrow c \rightarrow a \Rightarrow (b \Rightarrow c)$

Terminology:

- For $P \wedge Q$, P and Q are conjuncts
- For $P \vee Q$, P and Q are disjuncts
- For $P \Rightarrow Q$, P is the premise/antecedent/hypothesis, and Q is the consequent/conclusion
- The contrapositive of $p \Rightarrow q$ is $\neg q \Rightarrow \neg p$.

Prime Proposition: a proposition that cannot be broken down further (indecomposable).

Eg: "the snow is red"

Compound Proposition: a proposition that contains multiple prime propositions joined by connectives.

Eg: "the snow is red and the grass is green".

Formalizing Natural Language:

$\neg P$: not P, P does not hold, it is not the case

that P , P is false

$P \wedge Q$: P and Q , P but Q , P despite Q , not only P but Q , P while Q , P yet Q , P although Q .

$P \vee Q$: P or Q , P or Q or both, P "and/or" Q , P unless Q

$P \Rightarrow Q$: if P then Q , Q if P , P only if Q , Q when P , P is sufficient for Q , Q is necessary for P , P implies Q .

$P \Leftrightarrow Q$: P if and only if Q , P is necessary and sufficient for Q , P exactly if Q , P is exactly Q .

Example: formalize the following. Let c = "it is cold" and s = "it is snowing".

1) It is cold but it is not snowing
 $\hookrightarrow c \wedge \neg s$

2) It is cold only if it is snowing
 $\hookrightarrow s \Rightarrow c$

3) It is snowing only if it is cold
 $\hookrightarrow c \Rightarrow s$

Example: "it is not the case that I pass the course if I fail the exam". Let F be "I fail the exam" and C be "I pass the course".

↳ $F \Rightarrow \neg C$; "failing the exam implies not passing". or $\neg(F \Rightarrow C)$?

both seem viable, so let's use a truth table!

↓

F	C	$F \Rightarrow \neg C$	$\neg(F \Rightarrow C)$
0	0	1	0
0	1	1	1 → same!
1	0	1	0
1	1	0	0 → same!

more correct.

∴, $F \Rightarrow \neg C$.

- Sometimes, logical connectives don't exactly match their meanings in English.

↳ Eg: "the driver hit the cyclist and drove on" is very different to "the driver drove on and hit the cyclist", even though $P \wedge Q = Q \wedge P$. ↴ bc of the temporal (time) element!

Exclusive OR: $(P \vee Q) \wedge \neg(P \wedge Q)$

↳ Eg: "You may take Thursday off or you may take Friday off".

- We have to be careful of the meaning of implication.

↳ especially the "false implies anything" problem - if the antecedent is false, the implication is true.

- Classical logic is two-valued: the two possible truth values are T and F.

↳ T denotes the property of a formula being true.

↳ F denotes the property of a formula being false.

↳ the range of the semantic function for propositional logic is the set of truth values: $\text{Tr} = \{\text{T}, \text{F}\}$.

Boolean Valuation (BV): a function from the set of wffs in propositional logic to the set Tr.

↳ given a formula $p \wedge q$, we write $[p \wedge q]$ to mean "the meaning of the formula" in a certain boolean valuation. The $[]$ is a function mapping syntax to its value.

In all boolean valuations:

- [false] = F, [true] = T

- $[\neg p] = \text{NOT}([p])$

- For the connectives,

- $[p \wedge q] = [p] \text{ AND } [q]$

- $[p \vee q] = [p] \text{ OR } [q]$

- $[p \Rightarrow q] = [p] \text{ IMP } [q]$

- $[p \Leftrightarrow q] = [p] \text{ IFF } [q]$

↳ when describing a boolean valuation, we only need to describe the association of truth values with the proposition symbols.

Example: Show the truth value associated with the formulae $(p \Rightarrow q) \wedge r$ in the boolean valuation where $p = [T]$, $q = [F]$, and $r = [F]$.

$$\begin{aligned}
 [(p \Rightarrow q) \wedge r] &= [p \Rightarrow q] \text{ AND } [r] \\
 &= ([p] \text{ IMP } [q]) \text{ AND } [r] \\
 &= (T \text{ IMP } F) \text{ AND } F \\
 &= F \text{ AND } F \\
 &= F.
 \end{aligned}$$

↗ "can it be true?"

Satisfiability: a formula P is satisfiable if there is a boolean valuation such that $[P] = T$.

↗ "is it always true?"

Tautology: a formula P is a tautology (or valid) if $[P] = T$ for all Boolean valuations.

↳ Eg: $P \vee \neg P$

P	$\neg P$	$P \vee \neg P$
0	1	1
1	0	1

↳ Since the expression is true for all boolean valuations, it is a tautology (and is also obviously satisfiable).

↳ Eg: $\neg(p \wedge \neg q)$

↳ when $[P] = T$ and $[Q] = T$:

$\text{NOT}([P]) \text{ AND } \text{NOT}([Q])$

$\text{NOT}(T \text{ AND } \text{NOT}(T))$

$\text{NOT}(T \text{ AND } F)$

$\text{NOT}(F)$

T

since there is a boolean valuation for which the statement is true, it is satisfiable.

when $[P] = T$ and $[Q] = F$:

$\text{NOT}([P]) \text{ AND } \text{NOT}([Q])$

$\text{NOT}(T \text{ AND } \text{NOT}(F))$

$\text{NOT}(T \text{ AND } T)$

$\text{NOT}(T)$

F

since there is a boolean valuation for which the statement is false, it is not a tautology.

∴, the statement is satisfiable, but not a tautology!

• When a formula Q is a tautology, we write:

$\models Q$, which is pronounced "entails Q".

↳ \models is a meta-symbol, it's not a part of the syntax of propositional logic - it tells us something about a propositional logic formula.

Logical Implication: a formula P logically implies a formula Q if and only if, for all boolean valuations, if $[P] = T$, then $[Q] = T$.

↳ $P \models Q$, pronounced "P entails Q" or "P logically implies Q"

this can be generalized: a set of formulas P_1, P_2, \dots, P_n logically imply a formula Q if and only if, for all boolean valuations, if $[P_1] = T$ and $[P_2] = T$ and ... $[P_n] = T$ then $[Q] = T$.

↳ $P_1, P_2, \dots, P_n \models Q \rightarrow$ also called a valid argument.

↳ equivalent to saying $P_1 \wedge P_2 \wedge \dots \wedge P_n \models Q$, or also $\vdash P_1 \wedge P_2 \wedge \dots \wedge P_n \Rightarrow Q$!

Contradiction: a propositional formula A is a contradiction (or a falsehood) if $[A] = F$ for all boolean valuations.

↳ Eg: $P \wedge \neg P$.

Contingent: A contingent formula is one that is neither a tautology nor a contradiction.

↳ i.e. - has a mixture of Ts and Fs.

Logical Equivalence: two formulas, P and Q , are logically

equivalent if and only if $[P] = [Q]$ in all boolean valuations.

↳ $P \Leftrightarrow Q$, pronounced "P is logically equivalent to Q"

↳ $P \Leftrightarrow Q$ iff $\models P \Leftrightarrow Q$.

Consistency: a collection of formulas is consistent if there is a boolean valuation in which all the formulas are T.

↳ Example: are the following sentences consistent?

- 1) Sales of houses fall off if interest rates rise
- 2) Auctioneers aren't happy if sales of houses fall off.
- 3) Interest rates are rising.
- 4) Auctioneers are happy.

First, we must formalize these sentences:

- let s be "Sales of houses fall off"
- let r be "interest rates rise"
- let h be "auctioneers are happy".

∴ the formulas are:

$$1) r \Rightarrow s$$

$$2) s \Rightarrow \neg h$$

$$3) r$$

$$4) h$$

S	r	h	$r \Rightarrow s$	$s \Rightarrow \neg h$	r	h
0	0	0	1	1	0	0
0	0	1	1	0	0	1
0	1	0	0	0	1	0
0	1	1	0	1	1	1
1	0	0	1	1	0	0
1	0	1	1	0	0	1
1	1	0	1	1	1	0
1	1	1	1	1	1	1

↳ Since there's no boolean valuation for which each sentence is true, the set of formulas is inconsistent!

Example: is this formula satisfiable?:

$$\neg(p \Rightarrow q) \wedge \neg(\neg r \Rightarrow \neg p)$$

Since the "terms" are conjuncts, for the formula to be satisfiable, there needs to be some boolean valuation of p , q , and r , for which each term = T.

↳ for $\neg(p \Rightarrow q)$ to be T, $p \Rightarrow q$ must be F. This only occurs if $[P] = 1$ and $[Q] = 0$.

since $[P]$ must be 1, $\neg(\neg r \Rightarrow \neg p)$ can be written as $\neg(\neg r \Rightarrow \text{NOT}([T]))$.

$$\neg(\neg r \Rightarrow F) \quad \therefore, [r] = F.$$

We see that when $[p] = T$, $[q] = F$, and $[r] = F$, the formula evaluates to true. ∴, the formula is satisfiable!

Example: is $p \Rightarrow q$, $q \Rightarrow p \models q \wedge p$ a valid argument?

P	q	$p \Rightarrow q$	$q \Rightarrow p$	$q \wedge p$	
0	0	1	1	0	<i>this row is a counterexample!</i>
0	1	1	0	0	no, because $q \wedge p$
1	0	0	1	0	is not always 1
1	1	1	1	1	when $p \Rightarrow q$ and $q \Rightarrow p$ are both 1.

• We can use truth tables to check these properties, but since a truth table needs 2^n rows, they can be very tedious. Therefore, we can use proof theories to determine these properties.

↳ As long as the proof theory is sound, we can use it to determine tautologies and valid arguments.

Proof Theory: Transformational Proof

Transformational Proof: an algebraic manipulation of formulas in propositional logic following rules.

Formal definition: a transformational proof is a means of determining if two well-formed formulas, P and Q, are logically equivalent by the (repeated) exchange of subformulas of P for logically equivalent subformulas that result in P being transformed into Q.

- Each step must follow a logical law
- The logical laws are expressed using the symbol \leftrightarrow .
- Equivalences that we can derive using transformational proof are expressed using the symbol \leftrightarrow .

Transformational Proof Rules:

• Comm-assoc:

$$\hookrightarrow P \wedge Q \leftrightarrow Q \wedge P \rightarrow P \wedge (Q \wedge R) \leftrightarrow (P \wedge Q) \wedge R$$

$$\hookrightarrow P \vee Q \leftrightarrow Q \vee P \rightarrow P \vee (Q \vee R) \leftrightarrow (P \vee Q) \vee R$$

$$\hookrightarrow P \leftrightarrow Q \leftrightarrow Q \leftrightarrow P$$

- lem: $P \vee \neg P \leftrightarrow \text{true}$
- Contr: $P \wedge \neg P \leftrightarrow \text{false}$
- impl: $P \Rightarrow Q \leftrightarrow \neg P \vee Q$
- idemp: $P \vee P \leftrightarrow P, P \wedge P \leftrightarrow P$
- neg: $\neg(\neg P) \leftrightarrow P$
- simp1:
 - $\hookrightarrow P \wedge \text{true} \leftrightarrow P, P \vee \text{true} \leftrightarrow \text{true}$
 - $\hookrightarrow P \wedge \text{false} \leftrightarrow \text{false}, P \vee \text{false} \leftrightarrow P.$
- dm: $\neg(P \wedge Q) \leftrightarrow \neg P \vee \neg Q, \neg(P \vee Q) = \neg P \wedge \neg Q$
- distr:
 - $\hookrightarrow P \vee (Q \wedge R) \leftrightarrow (P \vee Q) \wedge (P \vee R)$
 - $\hookrightarrow P \wedge (Q \vee R) \leftrightarrow (P \wedge Q) \vee (P \wedge R)$
- Contrapos: $P \Rightarrow Q \leftrightarrow \neg Q \Rightarrow \neg P$
- equiv: $P \Leftrightarrow Q \leftrightarrow (P \Rightarrow Q) \wedge (Q \Rightarrow P)$
- Simp2:
 - $\hookrightarrow P \vee (P \wedge Q) \leftrightarrow P$
 - $\hookrightarrow P \wedge (P \vee Q) \leftrightarrow P$

Example: prove $\neg(\neg p \vee \neg(r \vee s)) \leftrightarrow p \wedge r \wedge s$

- 1) $\neg(\neg p \vee \neg(r \vee s))$
- 2) $\neg\neg p \wedge \neg\neg(r \vee s)$ by dm
- 3) $p \wedge \neg(r \vee s)$ by neg
- 4) $p \wedge (r \vee s)$ by neg
- 5) $p \wedge r \vee s$ by distr.

↗ aka prove simp2!

Example: prove that $p \vee p \wedge q \leftrightarrow p$

- 1) $p \vee p \wedge q$
- 2) $(p \vee p) \wedge (p \vee q)$ by distr
- 3) $p \wedge (p \vee q)$ by idemp
- 4) $(p \vee \text{false}) \wedge (p \vee q)$ by simp 1
- 5) $p \vee (\text{false} \wedge q)$ by distr
- 6) $p \vee \text{false}$ by simp 1
- 7) p by simp 1!

Example: prove $\neg((p \wedge q) \Rightarrow p) \leftrightarrow \text{false}$

↗ aka, prove that
it's a contradiction!

- 1) $\neg((p \wedge q) \Rightarrow p)$
- 2) $\neg(\neg(p \wedge q) \vee p)$ by impl
- 3) $\neg\neg(p \wedge q) \wedge \neg p$ by dm
- 4) $p \wedge q \wedge \neg p$ by neg
- 5) $q \wedge \text{false}$ by simp 1
- 6) false by simp 1

Example: prove $\neg\text{true} \leftrightarrow \text{false}$

- 1) $\neg\text{true}$
- 2) $\neg(p \vee \neg p)$ by lem
- 3) $\neg p \wedge \neg\neg p$ by dm
- 4) $\neg p \wedge p$ by neg
- 5) false by contr!

Example: $p \wedge (\neg(\neg q \wedge \neg p) \vee p) \leftrightarrow p$

- 1) $p \wedge (\neg(\neg q \wedge \neg p) \vee p)$

- 2) $p \wedge (\neg q \vee \neg p \vee p)$ by idm
- 3) $p \wedge (q \vee \neg p \vee p)$ by neg
- 4) $p \wedge (q \vee p \vee p)$ by neg
- 5) $p \wedge (q \vee p)$ by idemp
- 6) p by simp2.

Normal Forms:

- A literal that is a proposition symbol or the negation of a proposition symbol.
- A formula is in conjunctive normal form (CNF) if it is a conjunction of one or more clauses, where a clause is a disjunction of literals or a single literal.
- A formula is in disjunctive normal form (DNF) if it is a disjunction of one or more clauses, where a clause is a conjunction of literals or a single literal.

Example: are the following in CNF or DNF or both?

- 1) $(p \wedge q \wedge r) \vee (\neg q \wedge \neg r)$: DNF
- 2) $\neg(p \Rightarrow q) \wedge (r \Rightarrow q)$ neither (no implications allowed)
- 3) $p \wedge q \vee \neg q \vee \neg r$ DNF
- 4) $(p \vee q) \wedge \neg r$ CNF → think of it as \wedge true?
- 5) $p \vee q$ DNF, but also CNF as it is only one clause
- 6) $\neg(p \wedge q)$ neither, negation must be on the literal
- 7) $\neg p$ both
- 8) $p \wedge r \vee p \wedge (q \vee \neg r)$ neither

Converting Formulas to CNF:

- Remove all \Rightarrow and \Leftrightarrow using impl/equiv laws
- If the formula contains any negated compound subformulas, either remove the negation by using the negation law or use DM to push the negation in.
- Once a formula with no negated compound subformulas is found, use the following distributivity laws:
 - ↳ $A \vee (B \wedge C) \Leftrightarrow (A \vee B) \wedge (A \vee C)$
 - ↳ $(A \wedge B) \vee C \Leftrightarrow (A \vee C) \wedge (B \vee C)$
- Simplify so there are no repeated literals in a clause and no two clauses with the same literals.
 - ↳ note: true/false may only appear if they're the entire formula.

↳ Example: find the conjunctive normal form of
 $\neg((p \vee \neg q) \wedge \neg r)$

$$\neg((p \vee \neg q) \wedge \neg r)$$

- 1) $\neg(p \vee \neg q) \vee \neg \neg r$ by dm
- 2) $\neg(p \vee \neg q) \vee r$ by neg
- 3) $\neg p \wedge \neg \neg q \vee r$ by dm
- 4) $\neg p \wedge q \vee r$ by neg
- 5) $(\neg p \vee r) \wedge (q \vee r)$ by distr.

\therefore the CNF is $(\neg p \vee r) \wedge (q \vee r)$

Converting Formulas to DNF:

- Remove all \Rightarrow and \Leftrightarrow using impl/equiv laws

- If the formula contains any negated compound subformulas, either remove the negation by using the negation law or use DM to push the negation in.
- Once a formula with no negated compound subformulas is found, use the following distributivity laws:
 - ↳ $A \wedge (B \vee C) \leftrightarrow (A \wedge B) \vee (A \wedge C)$
 - ↳ $(A \vee B) \wedge C \leftrightarrow (A \wedge C) \vee (B \wedge C)$
- Simplify so there are no repeated literals in a clause and no two clauses with the same literals.
 - ↳ note: true/false may only appear if they're the entire formula.

- If a formula is in DNF, it's very easy to find a satisfying assignment, as we just need to satisfy one of the clauses.

Natural Deduction:

- Review: Argument \rightarrow a collection of formulas, one of which, referred to as the conclusion, is justified by the others, referred to as the premise(s).

↳ an argument is valid if in all Boolean valuations where the premises have the value T, the conclusion also has the truth value T.

↳ note: no premises implies the conclusion is a tautology ($\models Q$).

↳ generally, to prove an argument is invalid, we have to show the boolean valuation for which the

Argument does not hold.

Natural Deduction is a proof theory for proving the validity of an argument in propositional logic.

↳ it's a collection of rules, called inference rules, each of which allows us to infer new formulas from given formulas.

↳ a form of forward proof

• Inference Rules: a primitive valid argument form.

Each inference rule enables the elimination or the introduction of a logical connective.

↳ most inference rules have names that consist of:

- a logical connective

- a letter:

- ↳ "i" for introducing a formula that contains the connective

- ↳ "e" for eliminating (aka using) a formula that contains the connective

The formulas used in Natural Deduction are like "mini-arguments". Eg: and-i : $P, Q \vdash P \wedge Q$

and-e: $P \wedge Q \vdash P / P \wedge Q \vdash Q$

Summary of general Natural Deduction Rules:

Introduction (i):

↓

$\vdash P, Q \vdash P \wedge Q$

$\rightarrow \text{and-i}$

$P \vdash \neg\neg P$

$\rightarrow \text{not-not-i}$

$P \vdash P \vee Q$

$\rightarrow \text{or-i}$

$P \Rightarrow Q, Q \Rightarrow P \vdash P \Leftrightarrow Q$

$\rightarrow \text{iff-i}$

Elimination (e):

$\vdash P \wedge Q \vdash P$	$\rightarrow \text{and-e}$
$P \Rightarrow Q, P \vdash Q$	$\rightarrow \text{imp-e}$
$\neg\neg P \vdash P$	$\rightarrow \text{not-not-e}$
$P, \neg P \vdash Q$	$\rightarrow \text{not-e}$
$P \Leftrightarrow Q \vdash P \Rightarrow Q$	$\rightarrow \text{iff-e}$

Example: $a, \neg\neg(b \wedge c) \vdash \neg\neg a \wedge c$

- 1) a premise
- 2) $\neg\neg(b \wedge c)$ premise
- 3) $\neg\neg a$ by not-not-i on 1
- 4) $b \wedge c$ by not-not-e on 2
- 5) c by and-e on 4
- 6) $\neg\neg a \wedge c$ by and-i on 3, 5

Example: $a, a \Rightarrow b, b \Leftrightarrow c \vdash b \wedge c$

- 1) a premise
- 2) $a \Rightarrow b$ premise
- 3) $b \Leftrightarrow c$ premise
- 4) b by imp-e on 1, 2
- 5) $b \Rightarrow c$ by iff-e on 3

6) c by imp-e on 4,5

7) $b \wedge c$ by and-i on 4,6

↳ lets us skip one step using iff-e

Additional Rule: $P \Leftrightarrow Q, P \vdash Q \rightarrow \text{iff-mp}$

Example: $\neg\neg a \Leftrightarrow b \wedge c, a \vdash b \vee s$

1) $\neg\neg a \Leftrightarrow b \wedge c$ premise

2) a premise

3) $\neg\neg a$ by not-not-i on 2

4) $b \wedge c$ by iff-mp on 1,3

5) b by and-e on 4

6) $b \vee s$ by or-i on 5

must be false implies anything!
∴ premises must be a contradiction

Example: $\neg a \Leftrightarrow \neg b, \neg b \wedge a \vdash c$

1) $\neg a \Leftrightarrow \neg b$ premise

2) $\neg b \wedge a$ premise

3) $\neg b$ by and-e on 2

4) $\neg a$ by iff-mp on 1,3

5) a by and-e on 2

6) c by not-e on 4,5

Subordinate Proofs (subproofs): Start by choosing a formula that we assume is true within the subproof. Then we see what we can prove using our assumption.
↳ used by imp-i, raa, cases (defined later)

assume $R \{$

...

$\vdash R \Rightarrow Q$

$\rightarrow \text{imp-i}$

Q

}

Example: $b \Rightarrow c \vdash \neg c \Rightarrow \neg b$

1) $b \Rightarrow c$ premise

2) assume $\neg c \{$

3) $\neg b$ by imp-e on 1,2

}

4) $\neg c \Rightarrow \neg b$ by imp-i on 2-3.

Example: $a \Rightarrow (b \Rightarrow c), b \vdash a \Rightarrow c$

1) $a \Rightarrow (b \Rightarrow c)$ premise

2) b premise

3) assume $a \{$

4) $b \Rightarrow c$ by imp-e on 1,3

5) c by imp-e on 2,4

}

6) $a \Rightarrow c$ by imp-i on 3-5.

→ no premises, so must be tautology!

Example: $\vdash (c \Rightarrow d) \Rightarrow ((\neg c \Rightarrow \neg b) \Rightarrow (b \Rightarrow d))$

1) Assume $c \Rightarrow d \{$

2) Assume $\neg c \Rightarrow \neg b \{$

3) Assume $b \{$

4) $\neg c$ by imp-e on 2,3

5) c by not-not-e on 4

6) d by imp-e on 1,5

}

7) $b \Rightarrow d$ by imp-i on 3-6

}

8) $(\neg c \Rightarrow \neg b) \Rightarrow (b \Rightarrow d)$ by imp-i on 2-7

}

9) $(c \Rightarrow d) \Rightarrow ((\neg c \Rightarrow \neg b) \Rightarrow (b \Rightarrow d))$ by imp-i on 1-8.