

Artificial Intelligence I

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This summary is a living document, i.e. I may continue to revise, extend, and improve it over time as I refine my understanding or receive feedback.

If you find any mistakes, unclear explanations, or have suggestions for improvement, please [contact me](#).

1 Foundations

1.1 Mathematical Language

Def 1.1. Natural Language: A natural language is any form of spoken or signed means of communication that has evolved naturally in humans through use and repetition without conscious planning or premeditation.

Def 1.2. Domain of Discourse: The **set** of entities, objects, or concepts that a language, discussion, or formal system refers to. It specifies the scope within which terms, statements, and reasoning apply.

Def 1.3. Jargon (Terminology): A jargon (or terminology) is a **set** of specialized words or phrases (called technical terms or just terms) relating to concepts from a particular **domain of discourse**.

Def 1.4. Technical Language: A technical language is a **natural language** extended by a **terminology** and (possibly) special idioms, discourse markers, and notations.

Def 1.5. Stylized Language: Mathematicians use a stylized language that uses formulae to represent mathematical objects, uses math idioms for special situations (e.g. "iff", "hence", "let... be..., then..."), and classifies statements by role (e.g., definition, Lemma, Theorem, Proof, Example).

Def 1.6. Mathematical Vernacular: Specialized **technical language** used by mathematicians to express definitions, proofs, and reasoning. It combines natural language, standard mathematical idioms, and symbolic expressions into a coherent style for clear mathematical communication.

Def 1.7. Formulae: A mathematical formula can be a **mathematical statement** (clause) which can be true or false (e.g. $x > 5, 3 + 5 = 7$), or a **mathematical object** (e.g. $3, n, x^2 + y^2 + z^2, \int_1^0 x^{3/2} dx$)

Def 1.8. Sequence: **mathematical vernacular** uses the concept of sequences instead of lists. Sequences are usually finite, but can be infinite as well.

Def 1.9. Ellipses: **mathematical vernacular** uses ellipses (\dots) as a constructor for **sequences**. The meaning of an ellipsis is usually considered "obvious" and left for interpretation by the reader.

ellipses allow to write down large **objects** easily, examples:

- $1, \dots, n \rightsquigarrow$ the **sequence** of natural numbers between 1 and n in order.
- $1, 4, 9, 16, \dots \rightsquigarrow$ the **sequence** of squares in orders.
- $e_1, \dots, e_n \rightsquigarrow$ a **sequence** of **objects** e_i for $1 \leq i \leq n$

Def 1.10. Varieties of Mathematical Statements: **Mathematical statements** come in different epistemic varieties:

- **Definitions:** **statements** that introduce new global identifier for important **objects**
- **Assertions:** **statements** that state properties of **mathematical objects**
- **Examples:** **statements** that exhibit a witness for some property
- **Axioms:** **statements** that characterize the **objects** of a certain **domain of discourse** or theory. An axiom (postulate) is a statement about **mathematical objects** that we *assume* to be true.

Def 1.11. Pragmatic Categories of Mathematical Assertions: **Mathematical assertions** are pragmatically classified into categories:

- **proofs** are arguments that justify the truth of **statements** beyond any doubt. **Proofs** are not really **statements**, but we sometimes treat them together.
- **proposition** is a **statement** which is interesting in its own right.
- **lemma** is an easily proved **statement** which is helpful for proving other **propositions** and **theorems**, but is usually not particularly interesting in its own right. A **lemma** is an intermediate **theorem** that serves as part of a **proof** of a larger **theorem**.
- **theorem** is a more important **statement** than a **proposition** which says something definitive on the subject, and often takes more effort to prove than a **proposition** or **lemma**. A **theorem** is a **statement** about **mathematical object** that we *know* to be true.
- **corollary** is a quick consequence of a **proposition** or **theorem** that was proven recently. It is a **theorem** that follows directly from another **theorem**.

- **conjecture** is a **statement** that is thought to be provable, but has not been yet. A **conjecture** that is proven is a **theorem**

Def 1.12. Declaration: In **mathematical vernacular** we call a clause that introduce new identifiers together with some properties a declaration. For example Let $\epsilon, \delta > 0 \dots$

Def 1.13. Scope: The scope of an identifier is the part of an expression where the reference is valid; that is, where the identifier can be used to refer. In the other parts, the identifier may refer to a different entity, or to nothing at all (unbound)

Def 1.14. Definiendum: The definiendum is the symbol, expression, or term being introduced by a **definition**. It is the newly named **object** or concept.

Def 1.15. Definiens: The definiens is the symbol, expression, or construction that specifies the meaning of the **definiendum**. It explains what the **definiendum** denotes.

Def 1.16. Simple Definition: A **simple definition** introduces a new name (the **definiendum**) for an existing **object** or concept (the **definiens**). The definiendum must be new and must not occur in the definiens. We write simple definitions using $:=$ or $=:$, for example $\phi := 2$.

Def 1.17. Pattern Definition: A **pattern definition** introduces a new operator or **relation** by applying it to distinct pattern variables v_1, \dots, v_n . The **definiens** is an expression in these variables. Applying the operator to arguments a_1, \dots, a_n means substituting v_i by a_i in the definiens. We use $:=$ for operator definitions and \Leftrightarrow for relation definitions. Example:

$$A \cap B := \{x \mid x \in A \wedge x \in B\}.$$

Def 1.18. Implicit Definition: An **implicit definition** (definition by description) specifies a new name n (the **definiendum**) by giving a clause A such that we can prove unique existence $\exists^1 n. A$. If such a **proof** exists, n is **well-defined**. Example: the empty set Φ is implicitly defined by $\forall x. x \notin \Phi$. Another example: the exponential function is the unique $f : \mathbb{R} \rightarrow \mathbb{R}$ satisfying $f' = f$ and $f(0) = 1$.

Def 1.19. Example: An example E is a **mathematical statement** that consists of:

- symbol p for the **exemplandum** (plural: exemplanda): the property to be exemplified,
- the **exemplans** (plural: exemplantia): an expression A denoting a **mathematical object** that acts as witness object for the property p , and
- (optionally) a **justification** of E , i.e. a **proof** π that $p(A)$ holds in the current context.

Def 1.20. Counter Example: An **example** for the complement of the property p where π is a **proof** that $p(A)$ does not hold.

Def 1.21. Running Example: An **example** that is recalled time and again during an argument, applying the newly discovered knowledge to it, presumably to show how things work.

Note

An **example** (or even several) for a **mathematical statement** B do not constitute a **proof** for B . On the other hand, one **counter example** for a **mathematical statement** B does show that $\neg B$ is true ($\exists x. \neg A \equiv \neg(\forall x. A)$).

Def 1.22. Proof by Contradiction: A **proof by contradiction** assumes the negation $\neg A$ of the claim A and derives a contradiction from that assumption. Since $\neg A$ cannot be true, we infer $\neg\neg A$ and therefore A .

Def 1.23. Proof by Local Hypothesis: A **proof by local hypothesis** is a proof of an implication $A \rightarrow B$ where we temporarily assume A and derive B from that assumption. After the subproof is closed, the assumption A may no longer be used.

Def 1.24. Chaining: **Chaining** applies a general implication $A \rightarrow B$ to a specific instance A' obtained from A by substituting variables with concrete values. This allows us to conclude the corresponding instance B' obtained from B by the same substitution.

Def 1.25. Without Loss of Generality (WLOG): An **inference principle** used in **proofs** when a **statement** $Q(x)$ must be shown for all cases of x , but the different cases are equivalent by symmetry or trivial reduction. **Formally**, if the domain of x can be partitioned into cases A_1, \dots, A_k and it can be shown that:

- proving $Q(x)$ under one representative case A_i suffices, because
- for every other case A_j there is either a trivial **proof** of $Q(x)$ or a direct reduction to the representative case,

then we may assume A_i holds “without loss of generality”. This allows us to simplify the argument by only proving the representative case.

Note

WLOG Example. if we want to prove the property $Q(p)$ for all primes p . We know that every prime is either 2 (the only even prime) or an odd prime. If the case $p = 2$ is easy, and the general odd prime case is the only real work, then we can say:

WLOG, assume p is odd

This does not exclude the even case; it means we have already checked that the even case adds no new difficulty.

Def 1.26. Greek Alphabet: In [mathematical vernacular](#), Greek letters are used extensively to convey precise meanings. [Table 1](#) lists the Greek letters you are expected to recognize and write fluently.

Note

In addition, [table 2](#) shows the curly Roman and Fraktur letters, which are also standard in mathematical writing.

α	A	alpha	β	B	beta	γ	Γ	gamma
δ	Δ	delta	ϵ	E	epsilon	ζ	Z	zeta
η	H	eta	θ, ϑ	Θ	theta	ι	I	iota
κ	K	kappa	λ	Λ	lambda	μ	M	mu
ν	N	nu	ξ	Ξ	xi	\o	O	omicron
π, ϖ	Π	pi	ρ	P	rho	σ	Σ	sigma
τ	T	tau	ν	Υ	upsilon	φ, ϕ	Φ	phi
χ	X	chi	ψ	Ψ	psi	ω	Ω	omega

Table 1: Greek Alphabet

Roman	$A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z$
Fraktur	$\mathfrak{A}, \mathfrak{B}, \mathfrak{C}, \mathfrak{D}, \mathfrak{E}, \mathfrak{F}, \mathfrak{G}, \mathfrak{H}, \mathfrak{I}, \mathfrak{J}, \mathfrak{K}, \mathfrak{L}, \mathfrak{M}, \mathfrak{N}, \mathfrak{O}, \mathfrak{P}, \mathfrak{Q}, \mathfrak{R}, \mathfrak{S}, \mathfrak{T}, \mathfrak{U}, \mathfrak{V}, \mathfrak{W}, \mathfrak{X}, \mathfrak{Y}, \mathfrak{Z}$

Table 2: Roman and Fraktur Letters

1.2 Sets

Def 1.27. Set: A collection of different things (called **elements** or **members** of the set). We can represent **sets** by listing the **elements** within curly brackets, e.g. $\{a, b, c\}$ or by describing the **elements** via a property, e.g. $\{x \mid x \bmod 2 = 0\}$ (the **set** of even numbers). We can state **element**-hood ($a \in S$) or not ($b \notin S$)

Def 1.28. Set Equality: $A \equiv B := \forall x. x \in A \Leftrightarrow x \in B$

Def 1.29. Subset: $A \subseteq B := \forall x. x \in A \Rightarrow x \in B$

Def 1.30. Proper Subset: $A \subset B := (A \subseteq B) \wedge (A \neq B)$

Def 1.31. Super Set: $A \supseteq B := \forall x. x \in B \Rightarrow x \in A$

Def 1.32. Proper Superset: $A \supset B := (A \supseteq B) \wedge (A \neq B)$

Def 1.33. Set Union: $A \cup B := \{x \mid x \in A \vee x \in B\}$

Def 1.34. Set Intersection: $A \cap B := \{x \mid x \in A \wedge x \in B\}$

Def 1.35. Disjoint: Two **sets** A, B are **disjoint** iff $A \cap B = \emptyset$

Def 1.36. Set Difference: $A \setminus B := \{x \mid x \in A \wedge x \notin B\}$

Def 1.37. Power Set: $\mathcal{P}(A) := \{S \mid S \subseteq A\}$ (the set of all subsets)

Def 1.38. Cartesian Product: $A \times B := \{(a, b) \mid a \in A \wedge b \in B\}$, (a, b) is a pair

Def 1.39. Family: A **set** of **sets**

Def 1.40. Topology: A **family** of open **sets**

Def 1.41. Indexing Function: Let I and X be **sets**. A function $f : I \rightarrow X$ is called an indexing function. The set I is

called the index set. For each $i \in I$, we define $x_i := f(i)$, here i is called the index (or parameter) of x_i .

Def 1.42. Indexed Family: Given an indexing function $f : I \rightarrow X$, the set of values $f(I) = \{f(i) : i \in I\}$ is called an indexed family. It is often written as $(x_i)_{i \in I}$, $\langle x_i \rangle_{i \in I}$, or $\{x_i\}_{i \in I}$.

Def 1.43. Union over a Family: Let $(X_i)_{i \in I}$ be an indexed family, then $\bigcup_{i \in I} X_i := \{x \mid \exists i \in I. x \in X_i\}$

Def 1.44. Intersection over a Family: Let $(X_i)_{i \in I}$ be an indexed family, then $\bigcap_{i \in I} X_i := \{x \mid \forall i \in I. x \in X_i\}$

Def 1.45. n -fold Cartesian Product: $\prod_{i=1}^n X_i := X_1 \times \cdots \times X_n := \{\langle x_1, \dots, x_n \rangle \mid \forall i. 1 \leq i \leq n \Rightarrow x_i \in X_i\}$ where $\langle x_1, \dots, x_n \rangle$ is called an n -tuple.

Def 1.46. n -dim Cartesian Space: $X^n := \{\langle x_1, \dots, x_n \rangle \mid 1 \leq i \leq n \Rightarrow x_i \in X\}$ where $\langle x_1, \dots, x_n \rangle$ is called a vector.

Def 1.47. Size of a Set: The size $\Gamma(A)$ (or $|A|$) of a set A is the number of elements in A .

Def 1.48. Pairwise Disjoint: A family of sets is called pairwise disjoint or mutually disjoint, if any two of those sets are disjoint.

Def 1.49. Multiset: A multiset (or bag) is a generalization of a set where elements can appear more than once. Formally, a multiset \mathcal{M} over a domain D is a pair (D, m) , where $m : D \rightarrow \mathbb{N}$ is a function mapping each element $x \in D$ to its multiplicity (the number of occurrences).

Def 1.50. Multiset Membership: $x \in \mathcal{M} := m(x) > 0$

Def 1.51. Multiset Size: The size of a multiset $\mathcal{M} = (D, m)$, denoted $\Gamma(\mathcal{M})$, is the sum of the multiplicities of all its elements: $\Gamma(\mathcal{M}) = \sum_{x \in D} m(x)$.

Def 1.52. Multiset Sum (Union): The sum of two multisets $\mathcal{M}_1 = (D, m_1)$ and $\mathcal{M}_2 = (D, m_2)$, denoted $\mathcal{M}_1 \uplus \mathcal{M}_2$, is a multiset where the multiplicity of each element is the sum of its multiplicities: $m_{\uplus}(x) = m_1(x) + m_2(x)$.

Def 1.53. Multiset Equality: $\mathcal{M}_1 \equiv \mathcal{M}_2 := \forall x \in D. m_1(x) = m_2(x)$

1.3 Relations

Def 1.54. Relation: $R \subseteq A \times B$ is a (binary) relation between A and B

Def 1.55. Relation on: a relation $R \subseteq A \times B$ where $A = B$ is called a relation on A

Def 1.56. Total: A relation $R \subseteq A \times B$ is called total (left total) iff $\forall x \in A. \exists y \in B. (x, y) \in R$

Def 1.57. Converse Relation: $R^{-1} \subseteq B \times A := \{(y, x) \mid (x, y) \in R\}$ is the converse relation of R

Def 1.58. Relation Composition: The composition of $R \subseteq A \times B$ and $S \subseteq B \times C$ is defined as $R \circ S := \{(a, c) \in A \times C \mid \exists b \in B. (a, b) \in R \wedge (b, c) \in S\}$

A relation on A : $R \subseteq A \times A$ is called:

- reflexive on A , iff $\forall a \in A. (a, a) \in R$
- irreflexive on A , iff $\forall a \in A. (a, a) \notin R$
- symmetric on A , iff $\forall a, b \in A. (a, b) \in R \Rightarrow (b, a) \in R$
- asymmetric on A , iff $\forall a, b \in A. (a, b) \in R \Rightarrow (b, a) \notin R$
- antisymmetric on A , iff $\forall a, b \in A. (a, b) \in R \wedge (b, a) \in R \Rightarrow a = b$
- transitive on A , iff $\forall a, b, c \in A. (a, b) \in R \wedge (b, c) \in R \Rightarrow (a, c) \in R$
- equivalence relation on A , iff R is reflexive symmetric, and transitive

Def 1.59. Equality Relation: The equality relation is an equivalence relation on any set.

Def 1.60. Divides Relation: The divides relation on the integers is defined as $\mid \subseteq \mathbb{Z} \times \mathbb{Z}$, where $\mid = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid \exists k \in \mathbb{Z} : b = a \cdot k\}$. We write $a \mid b$ to denote $(a, b) \in \mid$ (read as "a divides b").

Def 1.61. Congruence Modulo: For a fixed $n \in \mathbb{N}$ with $n \geq 1$, the congruence modulo n relation on the integers is defined as

$$\equiv_n \subseteq \mathbb{Z} \times \mathbb{Z}, \quad \equiv_n = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid n \mid (a - b)\}.$$

We write $a \equiv b \pmod{n}$ to denote $(a, b) \in \equiv_n$ (read as "a is congruent to b modulo n").

Def 1.62. Partial Ordering (\preceq): A relation $R \subseteq A \times A$ is called a (non-strict) **partial ordering** on A , iff R is **reflexive**, **antisymmetric**, and **transitive** on A .

Def 1.63. Strict Partial Ordering (\prec): A relation $R \subseteq A \times A$ is called a **strict partial ordering** on A , iff R is **irreflexive**, and **transitive** on A .

Def 1.64. Comparable: In a **non-strict partial ordering**, two elements a, b are comparable if either $a \preceq b$ or $b \preceq a$. If neither holds, they are incomparable.

Def 1.65. Linear Order: A **partial ordering** is called linear (or total) on A , iff all **elements** in A are **comparable**, i.e. if $(x, y) \in R$ or $(y, x) \in R$ for all $x, y \in A$. For example, the \leq **relation** is a **linear order** on \mathbb{N} . However, the "divides" ($|$) **relation** is a **non-strict partial ordering** on \mathbb{N} that is not **linear** (e.g., neither $2 | 3$ nor $3 | 2$).

Def 1.66. Partially Ordered Set (Poset): A **Partially Ordered Set** (or **poset**) is a pair $\langle G, \preceq \rangle$ where G is a **set** and \preceq is a **non-strict partial ordering** on G .

Def 1.67. Least Element: Let $\langle G, \preceq \rangle$ be a **poset** and $T \subseteq G$. An **element** $t \in T$ is the **least** (or **smallest**, **minimal**, or \preceq -**minimal**) element of T iff $t \preceq t'$ for all $t' \in T$.

Def 1.68. Greatest Element: Let $\langle G, \preceq \rangle$ be a **poset** and $T \subseteq G$. An **element** $t \in T$ is the **greatest** (or **largest**, **maximal**, or \preceq -**maximal**) element of T iff $t' \preceq t$ for all $t' \in T$.

1.4 Functions

Def 1.69. Partial function: A **relation** $R \subseteq X \times Y$ is a **partial function** from X to Y ($f : X \rightharpoonup Y$) iff $\forall x \in X, \forall y_1, y_2 \in Y. ((x, y_1) \in R \wedge (x, y_2) \in R \Rightarrow y_1 = y_2)$ (i.e. there is at most one $y \in Y$ with $(x, y) \in f$)

Def 1.70. dom, codom: We call X the domain ($\text{dom}(f)$), and Y the codomain ($\text{codom}(f)$)

Def 1.71. Function Application: Instead of writing $(x, y) \in f$ we write $f(x) = y$

Def 1.72. Undefined: we call a **partial function** $f : X \rightharpoonup Y$ undefined at $x \in X$, iff $\forall y \in Y. (x, y) \notin f$ ($f(x) = \perp$).

Def 1.73. Function: A **partial function** $f : X \rightharpoonup Y$ is called a **function** (or **total function**) from X to Y iff it is a **total relation**. ($\forall x \in X. \exists^1 y \in Y : (x, y) \in f$)

Note

A **partial function** guarantees uniqueness, but not existence. So each x has at most one y (some might have none). A **total function** guarantees both uniqueness and existence (at most and at least \rightarrow exactly one)

A **function** $f : X \rightarrow Y$ is called

- **injective** iff $\forall x_1, x_2 \in X. f(x_1) = f(x_2) \Rightarrow x_1 = x_2$
- **surjective** iff $\forall y \in Y. \exists x \in X. f(x) = y$
- **bijective** iff f is **injective** and **surjective**

Def 1.74. Function Composition: If $f : A \rightarrow B$ and $g : B \rightarrow C$ are **functions**, then we call $g \circ f : A \rightarrow C; x \mapsto g(f(x))$ the composition of g and f (read g after f).

Def 1.75. Image and Preimage: Let $f : X \rightarrow Y$ be a **function**, $X' \subseteq X$ and $Y' \subseteq Y$, then we call

- $f(X') := \{y \in Y \mid \exists x \in X'. (x, y) \in f\}$ the **image** of X' under f ,
- $\text{Im}(f) := f(X)$ the **image** of f , and
- $f^{-1}(Y') := \{x \in X \mid \exists y \in Y'. (x, y) \in f\}$ the **preimage** of Y' under f .

Def 1.76. Cardinality: We say that a **set** A is **finite** and has **cardinality** $\Gamma(A) \in \mathbb{N}$, iff there is a **bijective function** $f : A \rightarrow \{n \in \mathbb{N} \mid n < \Gamma(A)\}$.

Def 1.77. Countably Infinite: We say that a **set** A is countably infinite, iff there is a **bijective function** $f : A \rightarrow \mathbb{N}$.

Def 1.78. Countable: A **set** A is called countable, iff it is **finite** or **countably infinite**.

Def 1.79. Curried Function Type: Let X, Y, Z be sets. An **uncurried function** is written as

$$f : X \times Y \rightarrow Z, \quad f(x, y) = E(x, y).$$

The same **function** can equivalently be written in *curried* form as

$$f : X \rightarrow Y \rightarrow Z, \quad f(x)(y) = E(x, y).$$

Thus in the curried notation the **function** takes one argument at a time: for $x \in X$, the value $f(x)$ is itself a **function** $Y \rightarrow Z$, and applying it to $y \in Y$ yields $f(x)(y) \in Z$.

Def 1.80. Invertible: Let A and B be **sets** and $f : A \rightarrow B$ a **function**, then f is called invertible, iff there is a **function** $g : B \rightarrow A$, such that $f \circ g = \text{Id}_B$. g is called the inverse function (or just inverse) of f and is written as f^{-1} .

1.5 Mathematical Structures

Def 1.81. Formulae: A mathematical formula can be a **mathematical statement** (clause) which can be true or false (e.g. $x > 5, 3 + 5 = 7$), or a **mathematical object** (e.g. $3, n, x^2 + y^2 + z^2, \int_1^0 x^{3/2} dx$)

Def 1.82. Mathematical Structure: A mathematical structure combines multiple **mathematical objects** (the components) into a new **object**. The components usually have names by which they can be referenced. Given a **definition** of a mathematical structure S , we say that any **object** that conforms to that is an instance of S .

Def 1.83. Group: A group is a **mathematical structure** $\langle G, \circ, e, .^{-1} \rangle$ that consists of:

- a base **set** G of **objects**,
- an operation $\circ : G \times G \rightarrow G$, such that $\forall a, b \in G. a \circ b \in G$ and $\forall a, b, c \in G. (a \circ b) \circ c = a \circ (b \circ c)$,
- a unit $e \in G$, such that $\forall a \in G. e \circ a = a \circ e = a$, and
- the inverse function $.^{-1} : G \rightarrow G$, such that $\forall a \in G. a \circ a^{-1} = a^{-1} \circ a = e$

An example of a **group** is the **set** $G = \mathbb{Z}$, with the operation $+ : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$; then $e = 0$ and $.^{-1}$ is $\lambda x \in \mathbb{Z}. -x$. We write it as $\langle \mathbb{Z}, +, 0, - \rangle$.

Question: can we do the same for multiplication where $e = 1$? If we think about it, we would be stuck on finding the $.^{-1}$ component of the group. What can we always multiply with any integer and get $e = 1$ back? Take for example 1, we can multiply it with $\frac{1}{1}$ (great!). Take -1 , we can multiply it with $\frac{1}{-1}$ (also great!). But take any other integer, e.g. 2, we must multiply it with $\frac{1}{2}$ to get 1 back, however, $\frac{1}{2} \notin \mathbb{Z}$, it is however $\in \mathbb{Q}$! The multiplicative group would only make sense iff $G = \mathbb{Q} \setminus \{0\}$. We write that as $\langle \mathbb{Q} \setminus \{0\}, *, 1, a \mapsto \frac{1}{a} \rangle$.

But we need some multiplication **structure** that works for \mathbb{Z} !

Def 1.84. Monoid: A monoid is a **mathematical structure** $\langle M, \circ, e \rangle$ that consists of:

- A base set M of **objects**,
- An operation $\circ : M \times M \rightarrow M$, such that for all $a, b \in M$, we have $a \circ b \in M$ (closure),
- Associativity: for all $a, b, c \in M$, $(a \circ b) \circ c = a \circ (b \circ c)$, and
- A unit element $e \in M$, such that for all $a \in M. e \circ a = a \circ e = a$.

Hence, the **mathematical structure** $\langle \mathbb{Z}, *, 1 \rangle$ is a **monoid** (a **group** missing an inverse function).

We saw that $\langle \mathbb{Z}, +, 0, - \rangle$ is a **group** under addition. And $\langle \mathbb{Z}, *, 1 \rangle$ is a **monoid** under multiplication. Now, we want to do everyday arithmetics with integers; we want expressions where we have additions and multiplication (e.g. $a * (b + c)$) which evaluates to $(a * b) + (a * c)$.

For that, we need a **mathematical structure** where both addition and multiplication live together.

Def 1.85. Ring: A ring is a **mathematical structure** $\langle R, +, 0, -, *, 1 \rangle$ consisting of:

- A base **set** R .
- An addition operation $+ : R \times R \rightarrow R$ such that $\langle R, +, 0, - \rangle$ is a **group** (called abelian **group**).
- A multiplication operation $* : R \times R \rightarrow R$ such that $\langle R, *, 1 \rangle$ is a **monoid**.
- Distributivity: for all $a, b, c \in R$, $a * (b + c) = (a * b) + (a * c)$, $(a + b) * c = (a * c) + (b * c)$

Hence, mixing components from the **group** $\langle \mathbb{Z}, +, 0, - \rangle$ and the **monoid** $\langle \mathbb{Z}, *, 1 \rangle$ leaves us with a **ring** $\langle \mathbb{Z}, +, 0, -, *, 1 \rangle$

Def 1.86. Magma: A magma is a **mathematical structure** $\langle M, \circ \rangle$ consisting of:

- A base **set** M , and

- A binary operation $\circ : M \times M \rightarrow M$.

Example: $\langle \mathbb{Z}, - \rangle$ (integers under subtraction). $\langle \mathbb{N}, + \rangle$ (natural numbers under addition)

Def 1.87. Semigroup: A semigroup (**magma** with associativity) is a **mathematical structure** $\langle S, \circ \rangle$ consisting of:

- A base **set** S ,
- A binary operation $\circ : S \times S \rightarrow S$, and
- Associativity: for all $a, b, c \in S$, $(a \circ b) \circ c = a \circ (b \circ c)$

Example: $\langle \mathbb{Z}, + \rangle$ (integers under addition).

1.6 Formal Languages and Grammars

Def 1.88. Alphabet: An alphabet is a **finite set**; we call each element $a \in A$ a **character**, and an n -tuple $s \in A^n$ a **string** (of length n over A). We often write a string $\langle c_1, \dots, c_n \rangle$ as " $c_1 \dots c_n$ ", for instance "**abc**" for $\langle a, b, c \rangle$

Def 1.89. Empty String: Let A be an **alphabet**, then $A^0 = \{\langle \rangle\}$, where $\langle \rangle$ is the unique 0-tuple. We consider $\langle \rangle$ as the string of length 0 and call it the **empty string** and denote it with ϵ .

Def 1.90. String Length: Given a string s , we denote its length with $|s|$.

Def 1.91. String Concatenation: The concatenation $\text{conc}(s, t)$ of two strings $s = \langle s_1, \dots, s_n \rangle \in A^n$ and $t = \langle t_1, \dots, t_m \rangle \in A^m$ is defined as $s + t$ or simply **st**

Def 1.92. Kleene Plus/Star: Let A be an **alphabet**, then we define the **sets**:

- $A^+ := \bigcup_{i \in \mathbb{N}^+} A^i$ (*nonempty strings*), and
- $A^* := A^+ \cup \{\epsilon\}$ (*strings*).

Def 1.93. Formal Language: A **set** $L \subseteq A^*$ is called a *formal language* over A . For example, If $A = \{a, b\}$ then:

$$A^* = \bigcup_{n=0}^{\infty} A^n$$

where $A^0 = \epsilon$, $A^1 = \{a, b\}$, $A^2 = \{a, b, ab, ba\}$, and so on ...

$$\begin{aligned} A^* &= \{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, aba, abb, \dots\} \\ A^+ &= \{a, b, aa, ab, ba, bb, aaa, aab, aba, abb, \dots\} \end{aligned}$$

A **formal language** might be $L = \{a, b, aab, bbb, \dots\}$

Def 1.94. Repeating Chars: We use $c^{[n]}$ for the string that consists of the character **c** repeated n times. **Examples:**

- Let $A = \{a, b\}$, $a^{[5]} = \text{"aaaaa"}$.
- The **set** $M := \{ba^{[n]} \mid n \in \mathbb{N}\}$ of strings that start with character **b** followed by an arbitrary numbers of **a**'s is a **formal language** over $A = \{a, b\}$

Note

A **formal language** might be infinite and even undecidable even if the **alphabet** A is **finite**. For example, let $A = \{a, b\}$ then the **formal language** $L = \{a, ab, bba\}$ is **finite** but the **formal language** $L = \{a^{[n]} \mid n \in \mathbb{N}\}$ is infinite.

Since we cannot list all strings in a **formal language** L because there are infinitely many, we need a **finite description** that can generate all strings in L . We need **Grammars**.

Def 1.95. Phrase Structure Grammar: A phrase structure grammar (*type 0 grammar, unrestricted grammar, grammar*) is a tuple $\langle N, \Sigma, P, S \rangle$ where

- N is a **finite set** of **nonterminal symbols**,
- Σ is a **finite set** of **terminal symbols**. (members of $N \cup \Sigma$ are called symbols).
- P is a **finite set** of **production rules**: pairs $p := h \rightarrow b$ (also written as $h \Rightarrow b$), where $h \in (\Sigma \cup N)^* N (\Sigma \cup N)^*$ and $b \in (\Sigma \cup N)^*$. The string h is called the **head** of p and b the **body**.

- $S \in N$ is a distinguished symbol called the **start symbol** (also **sentence symbol**).

The sets N and Σ are assumed to be **disjoint**. Any word $w \in \Sigma^*$ is called a **terminal word**.

Note

Production rules map strings with at least one **nonterminal** to arbitrary other strings

Notation: If we have n production rule $h \rightarrow b_i$ sharing a head, we often write $h \rightarrow b_1 | \dots | b_n$ instead.

Example: A simple grammar for english sentences:

```

S ::= NP Vi
NP ::= Article N
Article ::= the | a | an
N ::= dog | teacher | ...
Vi ::= sleeps | smells | ...

```

Def 1.96. Lexical: A **production rule** whose head is a single **nonterminal** and whose body consists of a single **terminal** is called **lexical** or a **lexical insertion rule**.

Def 1.97. Lexicon of a Grammar: The **subset** of **lexical rules** of a **grammar** G is called the **lexicon** of G

Def 1.98. Vocabulary: The **set** of body symbols are called the **vocabulary** (or the **alphabet**).

Def 1.99. Lexical Categories of a Grammar: The **nonterminals** that appear in the heads of **lexical rules** are called **lexical categories** of the **grammar**.

Def 1.100. Structural Rules: The non **lexicon production rules** are called **structural**.

Def 1.101. Phrasal categories: The **nonterminals** in the heads of **production rules** that expand into other **nonterminals** are called **phrasal** (**syntactic**) **categories**.

Def 1.102. G -Derivation: Given a **phrase structure grammar** $G := \{N, \Sigma, P, S\}$, we say G **derives** $t \in (\Sigma \cup N)^*$ from $s \in (\Sigma \cup N)^*$ in one step, iff there is a **production rule** $p \in P$ with $p = h \rightarrow b$ and there are $u, v \in (\Sigma \cup N)^*$, such that $s = uhv$ and $t = ubv$. We write $s \xrightarrow{p} t$ (or $s \xrightarrow{G} t$ if p is clear from the context) and use $\xrightarrow{*}$ for the **reflexive transitive closure** of \xrightarrow{G} . We call $s \xrightarrow{*} t$ a G -derivation of t from s .

Def 1.103. Sentential Form: Given a **phrase structure grammar** $G := \{N, \Sigma, P, S\}$, we say that $s \in (\Sigma \cup N)^*$ is a **sentential form** of G , iff $S \xrightarrow{*} s$

Def 1.104. Sentence: A **sentential form** that does not contain **nonterminals** is called a **sentence** of G , we also say that G **accepts** s . We say that G **rejects** s , iff it is not a sentence of G .

Def 1.105. Language Generation: The language $L(G)$ of G is the **set** of its **sentences**. We say that $L(G)$ is **generated** by G .

Def 1.106. Equivalent Grammars: We call two **grammars** **equivalent**, iff they have the same **languages**.

Def 1.107. Universal Grammar: A **grammar** G is said to be **universal** if $L(G) = \Sigma^*$

Def 1.108. Syntactic Analysis: Syntactic analysis (parsing / syntax analysis) is the process of analyzing a string of symbols, either in a **formal** or a **natural language** by means of a **grammar**.

Note

The shape of the **grammar** determines the size of its **language**

Def 1.109. Context-Sensitive: We call a **grammar** **context-sensitive** (or type 1), if the bodies of **production rules** have no less symbols than the heads.

Def 1.110. Context-Free: We call a **grammar** **context-free** (or type 2), iff the heads have exactly one symbol.

Def 1.111. Regular: We call a **grammar** **regular** (or type 3, or REG), if additionally the bodies are empty or consist of a **nonterminal**, optionally followed by a **terminal symbol**.

Note

By extension, a [formal language](#) L is called *context-sensitive / context-free / regular*, iff it is the [language](#) of a respective grammar. [Context-free grammars](#) are sometimes [CFGs](#) and context-free languages [CFLs](#).

1.7 Graphs and Trees

Def 1.112. Undirected Graph: An undirected graph is a pair $\langle V, E \rangle$ such that

- V is a [set](#) of [vertices \(nodes\)](#), and
- $E \subseteq \{ \{v, \bar{v}\} \mid v, \bar{v} \in V \wedge v \neq \bar{v} \}$ is the [set](#) of its [undirected edges](#).

Def 1.113. Directed Graph: A directed graph (digraph) is a pair $\langle V, E \rangle$ such that

- V is a [set](#) of [vertices \(nodes\)](#), and
- $E \subseteq V \times V$ is the [set](#) of its [directed edges](#).

Def 1.114. Indegree: Given a [directed graph](#) $\langle V, E \rangle$, the indegree $\text{indeg}(v)$ of a vertex $v \in V$ is defined as $\text{indeg}(v) = \Gamma(\{ w \mid (w, v) \in E \})$.

Def 1.115. Outdegree: Given a [directed graph](#) $\langle V, E \rangle$, the outdegree $\text{outdeg}(v)$ (branching factor) of a vertex $v \in V$ is defined as $\text{outdeg}(v) = \Gamma(\{ w \mid (v, w) \in E \})$.

Note

[directed graphs](#) are nothing else than [relations](#).

Def 1.116. Initial vs Terminal Node: Let $G = \langle V, E \rangle$ be a [directed graph](#), then we call a node $v \in V$

- **initial** (source of G), iff there is no $w \in V$ such that $(w, v) \in E$ (no predecessor)
- **terminal** (sink of G), iff there is no $w \in V$ such that $(v, w) \in E$ (no successor)

Def 1.117. Graph Isomorphism: Iff we can find a [bijection](#) $\psi : V \rightarrow \bar{V}$ between two graphs $G = \langle V, E \rangle$ and $\bar{G} = \langle \bar{V}, \bar{E} \rangle$ then we call them isomorphic. The [bijection](#) $\psi : V \rightarrow \bar{V}$ is defined as $(a, b) \in E \Leftrightarrow (\psi(a), \psi(b)) \in \bar{E}$ for [directed graph](#). And for [undirected graph](#) it is defined as $\{a, b\} \in E \Leftrightarrow \{\psi(a), \psi(b)\} \in \bar{E}$

Def 1.118. Equivalent Graphs: Two graphs G and \bar{G} are [equivalent](#) iff there is an [isomorphism](#) ψ between G and \bar{G} .

Def 1.119. Labeled Graph: A labeled graph G is a quadruple $\langle V, E, L, l \rangle$ where $\langle V, E \rangle$ is a graph and $l : V \cup E \rightarrow L$ is a [partial function](#) into a [set](#) L of labels.

Def 1.120. Paths in Graphs: Given a graph $G := \langle V, E \rangle$ we call a $n + 1$ -tuple $p = \langle v_0, \dots, v_n \rangle \in V^{n+1}$ a [path](#) in G iff $(v_{i-1}, v_i) \in E$ for all $1 \leq i \leq n$ and $n > 0$.

- We say that v_i are nodes on p and that v_0 and v_n are [linked](#) by p .
- v_0 and v_n are called the [start](#) and [end](#) of p (write $\text{start}(p)$ and $\text{end}(p)$), the other v_i are called [inner nodes](#) of p .
- n is called the [length](#) of p (write $\text{len}(p)$).
- We denote the [set](#) of paths in G with $\Pi(G)$.

Def 1.121. Cyclic Graphs: Given a [directed graph](#) $G = \langle V, E \rangle$, a [path](#) p is called [cyclic](#) iff $\text{start}(p) = \text{end}(p)$. A cycle $\langle v_0, \dots, v_n \rangle$ is called [simple](#), iff $v_i \neq v_j$ for $1 \leq i, j \leq n$ with $i \neq j$ (all inner nodes are distinct).

Def 1.122. DAG: A [directed graph](#) with no [cycles](#) is called [directed acyclic graph \(DAG\)](#).

Def 1.123. Node Depth: Let $G = \langle V, E \rangle$ be a [directed graph](#), then the depth $\text{dp}(v)$ of a vertex $v \in V$ is defined to be 0, iff v is a source of G and the supremum $\sup(\{ \text{len}(p) \mid \text{indeg}(\text{start}(p)) = 0 \wedge \text{end}(p) = v \})$ otherwise, i.e. the length of the longest [path](#) from a source of G to v (can be infinite).

Def 1.124. Graph Depth: Given a [directed graph](#) $G = \langle V, E \rangle$, the [depth](#) ($\text{dp}(G)$) of G is defined as the supremum $\sup(\{ \text{len}(p) \mid p \in \Pi(G) \})$, i.e. the maximal path length in G .

Def 1.125. Tree: A tree is a [DAG](#) $G = \langle V, E \rangle$ such that

- There is exactly one [initial node](#) $v_r \in V$ (called the [root](#))
- All nodes but the root have [indegree](#) of 1.

We call v the **parent** of w , iff $(v, w) \in E$ (w is a child of v). We call a node v a **leaf** of G , iff it is **terminal**, i.e. if it does not have children.

Note

For any node $v \in V$ except the root v_r , there is exactly one **path** $p \in \Pi(G)$ with $\text{start}(p) = v_r$ and $\text{end}(p) = v$.

2 Introduction

Def 2.1. Artificial intelligence (AI): The capability of computational systems to perform tasks typically associated with human intelligence, such as learning, reasoning, problem-solving, perception, and decision-making

Def 2.2. Symbolic AI: A subfield of [Artificial Intelligence \(AI\)](#) based on the assumption that many aspects of intelligence can be achieved by the manipulation of symbols, combining them into meaningful structures (expressions) and manipulating them (using processes) to produce new expressions.

Def 2.3. Statistical AI: Remedies the two shortcomings of [symbolic AI](#) approaches: that all concepts represented by symbols are crisply defined, and that all aspects of the world are knowable/representable in principle. Statistical AI adopts sophisticated mathematical models of uncertainty and uses them to create more accurate world models and reason about them.

Def 2.4. Subsymbolic AI (a.k.a connectionism/neural AI): A subfield of [AI](#) that posits that intelligence is inherently tied to brains, where information is represented by a simple sequence pulses that are processed in parallel via simple calculations realized by neurons, and thus concentrates on neural computing.

Def 2.5. Embodied AI: Posits that intelligence cannot be achieved by [reasoning](#) about the state of the world ([symbolically](#), [statistically](#), or [sub-symbolically](#)), but must be embodied i.e. situated in the world, equipped with a "body" that can interact with it via sensors and actuators. Here, the main method for realizing intelligent behavior is by learning from the world.

Def 2.6. Reasoning: The process of producing valid arguments and predictive world models. There are three forms of reasoning:

- **deductive reasoning** to produce new knowledge from existing knowledge. *Example:* All humans are mortal. Socrates is a human. Therefore, Socrates is mortal.
- **inductive reasoning** to produce knowledge from perception. *Example:* The sun has risen every morning in recorded history. Therefore, the sun will rise tomorrow.
- **abductive reasoning** to produce explanations for observations and given knowledge. *Example:* The grass is wet this morning. If it rained last night, that would explain it. Therefore, it probably rained.

Def 2.7. Inference: The act or process of reaching a **conclusion** about something from known facts or evidence (jointly called **premises**)

Def 2.8. Formal Logic: The science of [deductively](#) valid inferences, meaning arguments whose [conclusions](#) necessarily follow from their [premises](#) by virtue of their form (their structure), regardless of the topic.

Def 2.9. Agent: An agent is a [structure](#) $A := \langle \mathcal{P}, \mathcal{A}, f \rangle$ where:

- \mathcal{P} is a [set](#) of percepts
- \mathcal{A} is a [set](#) of actions
- f is a [function](#) $f : \mathcal{P}^* \rightarrow \mathcal{A}$ that maps from percepts to actions.

In other words, an agent is anything that perceives its environment via sensors and acts on it with actuators.

Def 2.10. Performance Measure: A [function](#) that evaluates a sequence of environments.

Def 2.11. Rational: An [agent](#) is called **rational**, if it chooses whichever action maximizes the expected value of the [performance measure](#) given the percept sequence to date.

Def 2.12. PEAS: To design [rational agents](#), we must specify the PEAS components: [Performance Measure](#), Environment, Actuators, and Sensors.

Def 2.13. Environment Types: For an [agent](#) a we classify the environment e of a by its **type**, which is one of the following. We call e

1. *fully observable*, iff the a 's sensors give it access to the complete state of the environment at any point in time; otherwise, we call it *partially observable*.
2. *deterministic*, iff the next state of the environment is completely determined by the current state and a 's actions; otherwise, *stochastic*.
3. *episodic*, iff a 's experience is divided into atomic episodes, where it perceives and then performs a single action, and the next episode does not depend on previous ones. Otherwise, *sequential*.
4. *dynamic*, iff the environment can change without an action performed by a ; otherwise, *static*. If the environment does not change but a 's performance measure does, we call e *semidynamic*.

5. *discrete*, iff the sets of e 's state and a 's actions are countable; otherwise, *continuous*.

6. *single-agent*, iff only a acts on e ; otherwise *multi-agent*.

Def 2.14. Reflex: An agent $\langle \mathcal{P}, \mathcal{A}, f \rangle$ is called a **reflex agent**, iff it only takes the last percept into account when choosing an action, i.e. $f(p_1, \dots, p_k) = f(p_k) \forall p_1 \dots p_k \in \mathcal{P}$

Def 2.15. Model-Based Agent: A model-based agent $\langle \mathcal{P}, \mathcal{A}, \mathcal{S}, \mathcal{T}, s_0, S, a \rangle$ is an agent $\langle \mathcal{P}, \mathcal{A}, f \rangle$ whose actions depend on:

- a **world model**: a set \mathcal{S} of possible states, and a start state $s_0 \in \mathcal{S}$.
- a **transition model** \mathcal{T} that predicts a new state $\mathcal{T}(s, a)$ from a state s and an action a .
- a **sensor model** S that given a state s and a percept p determines a new state $S(s, p)$.
- an **action function** $a : \mathcal{S} \rightarrow \mathcal{A}$ that given a state $s \in \mathcal{S}$ selects the next action $a \in \mathcal{A}$.

Note

If the agent is in state s then it took action a and now perceives p , then the agent state will become $s' = S(p, \mathcal{T}(s, a))$ and accordingly take action $a' = a(s')$.

Def 2.16. Goal Based Agent: A goal based agent $\langle \mathcal{P}, \mathcal{A}, \mathcal{S}, \mathcal{T}, s_0, S, a, \mathcal{G} \rangle$ is a **model based agent** with an explicit set of goals. It consists of:

- a set of internal states \mathcal{S} and an initial state $s_0 \in \mathcal{S}$,
- a transition model $\mathcal{T} : \mathcal{S} \times \mathcal{A} \rightarrow \mathcal{S}$,
- a state update function $S : \mathcal{P} \times \mathcal{S} \rightarrow \mathcal{S}$,
- a set of goals \mathcal{G} ,
- a goal conditioned action function $a : \mathcal{S} \times \mathcal{G} \rightarrow \mathcal{A}$ selecting an action given a state and the goals.

Def 2.17. Utility-Based Agent: A utility-based agent uses a world model along with a utility function that models its preferences among the states of that world. It chooses the action that maximizes the expected utility.

Def 2.18. Learning Agent: A learning agent is an agent that can improve its own behavior through experience. It is composed of four main components:

- the performance element, which selects actions based on the agent's current percepts and represents its existing knowledge or behavior,
- the learning element, which improves the performance element over time by analyzing feedback and identifying how to make better decisions,
- the critic, which evaluates the agent's performance according to a given performance standard and provides feedback to the learning element,
- the problem generator, which suggests new and informative actions or experiences that help the agent explore and learn more effectively.

Def 2.19. State Representation: We call a state representation **atomic**, iff it has no internal structure (black box). However, iff each state is characterized by attributes and their values then the representation is **factored**. A **structured** state representation is when include representations of objects, their properties and relationships.

3 General Problem Solving

Def 3.1. Search Problem: A search problem $\Pi := \langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{I}, \mathcal{G} \rangle$ consists of a set \mathcal{S} of states, a set \mathcal{A} of actions, and a transition model $\mathcal{T} : \mathcal{A} \times \mathcal{S} \rightarrow \mathcal{P}(\mathcal{S})$ that assigns to any action $a \in \mathcal{A}$ and state $s \in \mathcal{S}$ a set of successor states. Certain states in \mathcal{S} are designated as goal (terminal) states ($\mathcal{G} \subseteq \mathcal{S}$ with $\mathcal{G} \neq \emptyset$) and initial states $\mathcal{I} \subseteq \mathcal{S}$.

Def 3.2. Action Application: We say that an action $a \in \mathcal{A}$ is applicable in state $s \in \mathcal{S}$, iff $\mathcal{T}(a, s) \neq \emptyset$ and that any $s' \in \mathcal{T}(a, s)$ is a result of applying action a to state s . We call $\mathcal{T}_a : \mathcal{S} \rightarrow \mathcal{P}(\mathcal{S})$ with $\mathcal{T}_a(s) := \mathcal{T}(a, s)$ the result relation for a and $\mathcal{T}_{\mathcal{A}} := \bigcup_{a \in \mathcal{A}} \mathcal{T}_a$ the result relation of Π .

Def 3.3. State Space: The graph $\langle \mathcal{S}, \mathcal{T}_{\mathcal{A}} \rangle$ is called the state space induced by Π .

Def 3.4. Solution: A solution for Π consists of a sequence a_1, \dots, a_n of actions such that for all $1 < i \leq n$:

- a_i is applicable to state s_{i-1} where $s_0 \in \mathcal{I}$, and
- $s_i \in \mathcal{T}_{a_i}(s_{i-1})$, and $s_n \in \mathcal{G}$

Def 3.5. Cost Function: Often we add a cost function $c : \mathcal{A} \rightarrow \mathbb{R}_0^+$ that associates a step cost $c(a)$ to an action $a \in \mathcal{A}$. The cost of a solution is the sum of the step costs of its actions.

Note

- For deterministic environments, we have $|\mathcal{T}(a, s)| \leq 1$
- For fully observable ones, we have $\mathcal{I} = \{s_0\}$

Def 3.6. Successor Function/State: In a search problem, \mathcal{T}_a induces a partial function $S_a : \mathcal{S} \rightharpoonup \mathcal{S}$ whose natural domain is the set of states where a is applicable: $S_a(s) := s'$ if $\mathcal{T}_a = \{s'\}$ and undefined at s otherwise. We call S_a the successor function for a and $S_a(s)$ the successor state of s .

Note

- A search problem is called a single-state problem iff it is fully observable, deterministic, static, and discrete.
- A search problem is called a multi-state problem iff it is partially observable.
- A search problem is called a contingency problem iff the environment is non deterministic and the state space is unknown.

Def 3.7. Tree Search: Given a search problem $\Pi := \langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{I}, \mathcal{G} \rangle$, the tree search algorithm consists of the simulated exploration of the state space $\langle \mathcal{S}, \mathcal{T}_{\mathcal{A}} \rangle$ in a search tree formed by successively expanding already explored states.

Def 3.8. Path Cost: We define the path cost of a node n in a search tree T to be the sum of the step costs on the path from n to the root of T .

The general structure of Tree Search algorithms is as follows:

```
TREE_SEARCH(start, INSERT):
    fringe ← empty list
    append start to fringe
    while fringe is not empty:
        node ← remove first element of fringe
        if is_goal(node):
            return node
        children ← expand(node)
        INSERT(fringe, children)
    return failure
```

Def 3.9. Strategy: A strategy is a function that picks a node from the fringe of a search tree

Note

Every algorithm has its own strategy, hence the implementation of the INSERT differs based on that strategy.

Def 3.10. Properties of Strategies:

- completeness: does it always find a solution if one exists?
- optimality: does it always find the optimal solution (least cost)?

- time complexity: number of nodes the algorithm explores (expands)
- space complexity: maximum number of nodes in memory

Note

Time and space complexity measured in terms of:

- b : maximum branching factor of the search tree
- d : minimal graph depth of a solution in the search tree
- m : maximum graph depth of the search tree

Def 3.11. Breadth-First Search (BFS): The BFS strategy treats the fringe as a FIFO queue, i.e. successors go in at the end (back) of the fringe.

BFS Properties Analysis

- Time Complexity:

assume we have a binary search tree ($b = 2$) and we found solution in depth = 3. In the 0th level we explored $2^0 = 1$ nodes. In the 1st level, $2^1 = 2$ nodes. In the 2nd level, $2^2 = 4$ nodes. And finally $2^3 = 8$ nodes in the third level. Number of nodes the algorithm explored will be $2^0 + 2^1 + 2^2 + 2^3$.

– Generally, for arbitrary b, d , we have $1 + b + b^2 + \dots + b^d$, which means, worst time complexity is $\mathcal{O}(b^d)$ (exponential in d).

- The space complexity is also $\mathcal{O}(b^d)$.
- BFS is complete if: (i) b is finite, and (ii) the state space is finite or has a solution.
- BFS is optimal if we have a uniform constant cost for all actions.

Def 3.12. Uniform-Cost Search (UCS): UCS is the strategy where the fringe is ordered by increasing path cost. (*expands least cost first*)

Note

UCS it is equivalent to BFS if all costs are equal

UCS Properties Analysis

- Time and space complexity $\approx \mathcal{O}(b^d)$
- UCS is complete if:
 - b is finite
 - all actions costs are $\geq \epsilon > 0$
 - state space is finite or has a solution.

Def 3.13. Depth-First Search (DFS): DFS is the strategy where the fringe is organized as a LIFO stack, i.e. successors go in at the front of the fringe.

Def 3.14. Backtracking: Every node that is pushed to the stack is called a **backtrack point**. Popping a non-goal node from the stack and continuing the search with the new top element is called **backtracking**. For this reason, the **DFS algorithm** is also referred to as a **backtracking search**.

DFS Properties Analysis

- Time complexity is $\mathcal{O}(b^m)$ (exponential in the maximum depth)
- Space complexity is linear. While BFS keeps track of all nodes at the current level in memory, DFS needs to only keep the current path (from root to m), and also needs to keep the remaining unexplored sibling root node for each node along that path (to backtrack). This means, for each level, we store the siblings, i.e. b nodes. We explore until we hit the max depth m and in each level we store b . Hence we have a linear space $\mathcal{O}(b \cdot m)$
- DFS is complete if the search tree is finite and acyclic.
- DFS is not optimal.

Def 3.15. Depth-Limited Search (DLS): DLS is a [DFS](#) with a depth limit l . We treat all nodes at depth l as if they have no children.

DLS Properties Analysis

- Time complexity $\sim \mathcal{O}(b^l)$
- Space complexity $\sim \mathcal{O}(b \cdot l)$
- Not complete (solution maybe beyond chosen l)
- Not optimal

Def 3.16. Iterative Deepening Search (IDS): IDS is a [DLS](#) with an ever-increasing depth limit. We call the difference between successive depth limits the step size.

Note

- [IDS](#) solves the problem of choosing a good l in [DLS](#).
- [IDS](#) tries all values until either a [solution](#) is found (depth is returned to [DLS](#), we call that the cutoff value) or we return failure.
- [IDS](#) combines benefits of [DFS](#) and [BFS](#).

IDS Properties Analysis

It is similar to [DFS](#) in memory requirements (assuing [finite](#) and [acyclic search tree](#)).

- $\mathcal{O}(b \cdot d)$ when there is a [solution](#)
- $\mathcal{O}(b \cdot m)$ when there is no [solution](#)

It is similar to [BFS](#) in terms of optimality, completeness, and time complexity. Optimal for problems where all actions have the same cost. Complete if b is [finite](#) and the [state space](#) is finite or has a solution.

With regard to time complexity, consider [IDS](#) finds a solution at depth d , then:

- nodes at the very bottom (d) are visited only once in the final iteration.
- nodes at $d - 1$ are visited twice, once in the search with depth $d - 1$ and once in the search with depth d .
- nodes at $d - 2$ are visited three times
- and so son, until root node ($d = 0$) which is visited d times.

Generally, we have $(d)b^1 + (d-1)b^2 + (d-2)b^3 + \dots + b^d$. However, the majority of nodes are at the max depth where there are b^d nodes. Those are only visited once and the extra cost of visiting shallower nodes does not significantly increase the overall count. Therefore, time complexity is bounded by b^d ($\mathcal{O}(b^d)$) because b^d dominates the total nodes count in a large [search space](#).

Def 3.17. Graph Search: A graph search algorithm is a variant of a [tree search algorithm](#) that prunes nodes whose state has already been considrerred (duplicate pruning), essentially using a [DAG](#) data strucutre.

The general structure of [Graph Search](#) algorithms is as follows:

```
GRAPH_SEARCH(start, INSERT):
    fringe ← empty list
    visited ← empty set
    append start to fringe
    add state(start) to visited
    while fringe is not empty:
        node ← remove first element of fringe
        if is_goal(node):
            return node
        children ← expand(node)
        for each child in children:
            if state(child) not in visited:
                add state(child) to visited
                INSERT(fringe, child)
    return failure
```

Def 3.18. Search Alrogorithm: We speak of a **search algorithm** when we do not want to distinguish whether it is a **tree** or a **graph search algorithm** - *difference considered as an implementation detail.*

Def 3.19. Informed: A **search algorithm** is called **informed**, iff it uses some form of external information to guide the search.

Def 3.20. Evaluation Function: An evaluation function assigns a desirability value to each node of the **search tree**. It is not part of the **search problem**, but must be added externally.

Def 3.21. Best-First Search: In best-first search, the fringe is a queue sorted in decreasing order of desirability.

Def 3.22. Heuristic: A heuristic is an **evaluation function** h on states that estimates the **cost** from n to the nearest goal state. We speak of **heuristic search** if the **search algorithm** uses a heuristic in some way.

Def 3.23. Greedy Search: A **best-first search strategy** where the fringe is organized as a queue sorted based on h value.

Greedy Search Properties

- Time and space complexity are both exponential in m (max depth) $\rightsquigarrow \mathcal{O}(b^m)$
- It is not optimal. But it is complete if the **state space** is finite.

Def 3.24. Heuristic Function: A heuristic funciton for **search problem** Π is a **function** $h : \mathcal{S} \rightarrow \mathbb{R}_0^+ \cup \{\infty\}$ so that $h(s) = 0 \quad \forall s \in \mathcal{G}$.

Def 3.25. Goal Distance Function: The **function** $h^* : \mathcal{S} \rightarrow \mathbb{R}_0^+ \cup \{\infty\}$, where $h^*(s)$ is the **cost** of a cheapest **path** from s to a goal state, or ∞ if no such path exists. (*the perfect heuristic which we do not know and cannot compute*)

Def 3.26. Admissible: For a **search problem** Π with states \mathcal{S} and actions \mathcal{A} . We say that a **heuristic** h for Π is **admissible** if

$$h(s) \leq h^*(s) \quad \forall s \in \mathcal{S}$$

Note

Admissible heuristics never overestimates; our guess should be always optimistic or exact, never too high

Def 3.27. Consistent: For a **search problem** Π with states \mathcal{S} and actions \mathcal{A} . We say that a **heuristic** h for Π is **consistent** if

$$h(s) - h(s') \leq c(a) \quad \forall s \in \mathcal{S}, a \in \mathcal{A}, s' \in \mathcal{T}(s, a)$$

Note

A **consistent heuristic** never drops faster than the real cost you pay when moving through the state space. Formally, for every transition $s \xrightarrow{a} s'$,

$$h(s) \leq c(a) + h(s')$$

This means the heuristic respects a triangle inequality with respect to the actual **step costs**. Consistency ensures that the estimated **total cost** along a **path** never decreases.

Def 3.28. A* Evaluation Function: Given a **path cost** function g and a **heuristic** h , the **A* evaluation function** is

$$f(n) = g(n) + h(n).$$

It estimates the total cost of a cheapest path from the **start state** to a goal via n .

Def 3.29. A* Search: A* search is the **best-first search** strategy that uses the **A* evaluation function** $f = g + h$ to order the fringe.

Theorem 3.1. **A* Search** with **admissible heuristic** is optimal

Def 3.30. Dominance: Let h_1 and h_2 be two **admissible heuristic**, we say that h_2 **dominates** h_1 if $h_2(s) \geq h_1(s) \quad \forall s \in \mathcal{S}$.

Theorem 3.2. If h_2 **dominates** h_1 , then h_2 is better for **search** than h_1

Proof. If h_2 dominates h_1 , then h_2 is closer to h^* than h_1 □

Def 3.31. Adversarial Search: An adversarial search problem is a [search problem](#) $\langle \mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{I}, \mathcal{G} \rangle$, where:

- $\mathcal{S} = \mathcal{S}^{\text{Max}} \uplus \mathcal{S}^{\text{Min}} \uplus \mathcal{G}$
- $\mathcal{A} = \mathcal{A}^{\text{Max}} \uplus \mathcal{A}^{\text{Min}}$
- For $a \in \mathcal{A}^{\text{Max}}$, if $s \xrightarrow{a} s'$, then $s \in \mathcal{S}^{\text{Max}}$ and $s' \in (\mathcal{S}^{\text{Min}} \cup \mathcal{G})$
- For $a \in \mathcal{A}^{\text{Min}}$, if $s \xrightarrow{a} s'$, then $s \in \mathcal{S}^{\text{Min}}$ and $s' \in (\mathcal{S}^{\text{Max}} \cup \mathcal{G})$

together with a **game utility function** $u : \mathcal{G} \rightarrow \mathbb{R}$

Def 3.32. Strategy: Let Θ be an [adversarial search problem](#), and let $X \in \{\text{Max}, \text{Min}\}$. A **strategy** for X is a [function](#) $\sigma^X : \mathcal{S}^X \rightarrow \mathcal{A}^X$ so that $a \in \mathcal{A}^X$ is [applicable](#) to $s \in \mathcal{S}^X$ whenever $\sigma^X(s) = a$.

Def 3.33. Optimal Strategy: A [strategy](#) is called **optimal** if it yields the best possible [utility](#) for X assuming perfect opponent play.

Note

Assumptions for Adversarial Games:

- Two players acting in strictly alternating turns
- Fully observable and deterministic game states
- Finite state space so the game tree is finite
- Terminal states have a real-valued utility
- The game is zero-sum: Max maximizes the utility, Min minimizes the same utility

Def 3.34. Minimax: Let Θ be an [adversarial search problem](#) with [utility function](#) $u : \mathcal{G} \rightarrow \mathbb{R}$. The **minimax value** is the [function](#) $\hat{u} : \mathcal{S} \rightarrow \mathbb{R}$ defined by:

$$\hat{u}(s) = \begin{cases} u(s) & \text{if } s \in \mathcal{G}, \\ \max_{s' \in \mathcal{T}(a,s)} \hat{u}(s') & \text{if } s \in \mathcal{S}^{\text{Max}}, \\ \min_{s' \in \mathcal{T}(a,s)} \hat{u}(s') & \text{if } s \in \mathcal{S}^{\text{Min}}, \end{cases}$$

where a ranges over all actions [applicable](#) to s . The **minimax decision** at a root state r is any action whose [successor state](#) achieves $\hat{u}(r)$.

Def 3.35. Minimax Algorithm: The minimax algorithm is given by the following recursive function whose arguments are a node (state) and whether it is Max's turn or Min's.

```
function MINIMAX(node, maximizing):
    if TERMINAL(node):
        return UTILITY(node)

    if maximizing:
        best = -infinity
        for each child in SUCCESSORS(node):
            val = MINIMAX(child, false)
            if val > best:
                best = val
        return best

    else:
        best = +infinity
        for each child in SUCCESSORS(node):
            val = MINIMAX(child, true)
            if val < best:
                best = val
        return best
```

Def 3.36. Evaluation Function: In practice, full-depth [minimax](#) is infeasible because the [search tree](#) is too large. We therefore impose a fixed *depth limit / horizon* d and stop the search at all states $\{s \in \mathcal{S} \mid \text{dp}(s) = d\}$, called *cut-off states*.

An evaluation function is a [function](#) $f : \mathcal{S} \rightarrow \mathbb{R}$ that assigns a numerical estimate of the true [minimax value](#) $\hat{u}(s)$ to any nonterminal cut-off state s . If a cut-off state is terminal, its utility $u(s)$ is used instead of $f(s)$.

Def 3.37. Alpha Value: For each node n in a [minimax search tree](#), the alpha value $\alpha(n)$ is the highest Max-node utility that search has encountered on its [path](#) from the [root](#) to n .

Def 3.38. Beta Value: For each node n in a [minimax search tree](#), the beta value $\beta(n)$ is the highest Min-node utility that search has encountered on its [path](#) from the [root](#) to n .

Def 3.39. Alpha-Beta Pruning: Alpha-beta pruning is a variant of [minimax](#) that avoids exploring branches that cannot change the [minimax value](#).

- At a Max-node n , if a successor s is found with utility $\hat{u}(s) \geq \beta(n)$, then no remaining successors of n can affect its value and they are pruned.
- At a Min-node n , if a successor s is found with utility $\hat{u}(s) \leq \alpha(n)$, then no remaining successors of n can affect its value and they are pruned.

The algorithm returns the same [minimax value](#) as full search while expanding fewer nodes.

```
function ALPHABETA(node, alpha, beta, maximizing):
    if TERMINAL(node):
        return UTILITY(node)

    if maximizing:
        best = -infinity
        for each child in SUCCESSORS(node):
            val = ALPHABETA(child, alpha, beta, false)
            if val > best:
                best = val
            if best > alpha:
                alpha = best
            if beta <= alpha:
                break
        return best

    else:
        best = +infinity
        for each child in SUCCESSORS(node):
            val = ALPHABETA(child, alpha, beta, true)
            if val < best:
                best = val
            if best < beta:
                beta = best
            if beta <= alpha:
                break
        return best
```

4 Constraint Satisfaction Problems

Def 4.1. Constraint Satisfaction Problem (CSP): A triple $\gamma := \langle V, D, C \rangle$ where

- V is a finite set of variables,
- D is an V -indexed family of domains: $(D_v)_{v \in V}$
- C is the set of constraints. For a subset $\{v_1, \dots, v_k\} \subseteq V$, a constraint $C_{\{v_1, \dots, v_k\}} \subset D_{v_1} \times \dots \times D_{v_k}$

Def 4.2. Variable Assignment: We call a partial function:

$$\varphi : V \rightharpoonup \bigcup_{v \in V} D_v$$

a **variable assignment** if $\varphi(v) \in D_v \quad \forall v \in \text{dom}(\varphi)$

Def 4.3. Satisfying Assignment: a variable assignment φ satisfies a constraint $C_{\{v_1, \dots, v_k\}}$ iff $(\varphi(v_1), \dots, \varphi(v_k)) \in C_{\{v_1, \dots, v_k\}}$.

Def 4.4. Consistent Assignment: a variable assignment φ is called **consistent** iff it satisfies all constraints in C .

Def 4.5. Legal Assignment: A value $d \in D_v$ is called **legal** for a variable $v \in V$ iff $v \mapsto d$ is a **consistent assignment**; otherwise, **illegal**.

Def 4.6. Conflicted: A variable with an **illegal value** under **assignment** φ is called **conflicted**.

Def 4.7. CSP Solution: A variable assignment that is **total** (i.e. **function**) and **consistent** is a **solution** for the **CSP**.

Def 4.8. Satisfiable: A **CSP** γ is called **satisfiable** iff it has a **solution** (a total variable assignment φ that **satisfies** all constraints).

Def 4.9. Discrete: We call a **CSP** **discrete** iff all of the variables have **countable domains**; otherwise, **continuous**.

Def 4.10. Boolean CSP: A discrete **CSP** is called **boolean** iff $|D_v| = 2 \quad \forall v \in V$.

Note

Discrete **CSPs** with **domain size** d and n variables has a **search space** of size d^n , so a naive solve (brute-force) is worst case $\mathcal{O}(d^n)$. In general, deciding solvability of a **finite-domain CSP** is NP-complete.

Def 4.11. Constraint Order (Arity): Let $\gamma = \langle V, D, C \rangle$ be a **CSP**. For a constraint

$$C_{\{v_1, \dots, v_k\}} \subseteq D_{v_1} \times \dots \times D_{v_k},$$

its **order** (or *arity*) is

$$\text{ord}(C_{\{v_1, \dots, v_k\}}) := k.$$

The order of γ is

$$\max_{C_{\{v_1, \dots, v_k\}} \in C} k.$$

A constraint of order 1 is *unary*, order 2 is *binary*, and any constraint with order > 2 is *higher order*.

Def 4.12. Binary: A **binary CSP** is a **CSP** where each constraint is **unary** or **binary**.

Def 4.13. Constraint Graph: A **binary CSP** forms a **graph** called the **constraint graph** whose nodes are variables, and whose edges represent the constraints.

Def 4.14. Constraint Network: A constraint network is a **CSP** $\gamma := \langle V, D, C \rangle$ of **order** 2, hence, we write a **unary constraint** as C_v (representing $C_{\{v\}}$) and a **binary constraint** as C_{uv} (representing $C_{\{u, v\}}$). Note that $C_{uv} = C_{vu}$.

Note

The **constraint graph** where all constraints are **binary** is the **undirected graph**:

$$\langle V, \{(u, v) \in V^2 \mid C_{uv} \neq D_u \times D_v\} \rangle$$

CSP as Search

We can induce a **search problem** $\Pi_\gamma := \langle \mathcal{S}_\gamma, \mathcal{A}_\gamma, \mathcal{T}_\gamma, \mathcal{I}_\gamma, \mathcal{G}_\gamma \rangle$ from the **constraint network** $\gamma := \langle V, D, C \rangle$.

We define the **set** of states \mathcal{S}_γ as the **set** of all **partial assignments**:

$$\mathcal{S}_\gamma := \left\{ \varphi : V \rightharpoonup \bigcup_{v \in V} D_v \mid \varphi(v) \in D_v \quad \forall v \in \text{dom}(\varphi) \right\}$$

We define goal states \mathcal{G}_γ as the **set** of **total** and **consistent assignments**

$$\mathcal{G}_\gamma := \left\{ \varphi : V \rightarrow \bigcup_{v \in V} D_v \mid (\varphi(v) \in D_v \quad \wedge \quad (\varphi(u), \varphi(v)) \in C_{uv}) \quad \forall u, v \in V \right\}$$

The initial state is when we have no **assignments**:

$$\mathcal{I}_\gamma := \left\{ \varphi : V \rightharpoonup \bigcup_{v \in V} D_v \mid \text{dom}(\varphi) = \emptyset \right\}$$

Actions represent **assignments** as pairs:

$$\mathcal{A}_\gamma := \{(v, d) \mid v \in V \wedge d \in D_v\}$$

Transition model, given a current state s and an action $a = (v, d)$ gives us the successor state s' .

$$\mathcal{T}_\gamma : \mathcal{A}_\gamma \times \mathcal{S}_\gamma \rightarrow \mathcal{P}(\mathcal{S}_\gamma)$$

Concretely: $\mathcal{T}_\gamma((v, d), s) := \{s'\}$ where s' is the successor state (we are updating the **variable assignment**) which will evaluate as follows:

$$s'(w) := \begin{cases} d, & \text{if } w = v \\ s(w), & \text{if } w \in \text{dom}(s) \text{ and } w \neq v \end{cases} \quad \text{and} \quad \text{dom}(s') := \text{dom}(s) \cup \{v\}.$$

Def 4.15. Backtracking Search: Backtracking search is the basic uninformed algorithm for solving CSPs. It is DFS with two improvements, namely:

1. One variable at a time
 - variable assignments are commutative, fixing the order saves us time!
 - i.e. starting from state(WA=red) → state(WA=red, NT=green) is the same as starting from state(NT=green) → state(NT=green, WA=red)¹
 - We only need to consider assignments to a single variable at each step
2. Check constraints as you go
 - Consider only values which do not conflict previous assignments
 - That is not a goal test! We can think about it as incremental goal test.

The pseudocode for backtracking search is shown in [Algorithm 1](#)

Algorithm 1 Backtracking Search

```

1: function BACKTRACKING-SEARCH(csp)
2:   return RECURSIVE-BACKTRACKING({}, csp)
3: end function
4: function RECURSIVE-BACKTRACKING(assignment, csp)
5:   if assignment is complete then
6:     return assignment
7:   end if
8:   var ← SELECT-UNASSIGNED-VARIABLE(Variables[csp], assignment, csp)
9:   for each value in ORDER-DOMAIN-VALUES(var, assignment, csp) do
10:    if value is consistent with assignment given Constraints[csp] then
11:      add {var = value} to assignment
12:      result ← RECURSIVE-BACKTRACKING(assignment, csp)
13:      if result ≠ failure then
14:        return result
15:      end if
16:      remove {var = value} from assignment
17:    end if
18:   end for
19:   return failure
20: end function

```

Note

Note that the exact behaviors of the function: SELECT-UNASSIGNED-VARIABLE and ORDER-DOMAIN-VALUES are not specified yet

Def 4.16. Forward Checking: Forward checking is a filtering (inference) technique that improves the general uninformed backtracking search. It propagates information about illegal values. Whenever a variable $v \in V$ is assigned by $d \in D_v$ ($\varphi(v) = d$), we delete all values that are inconsistent with $\varphi(v)$ from every D_u for all variables u connected with v by a constraint.

Note

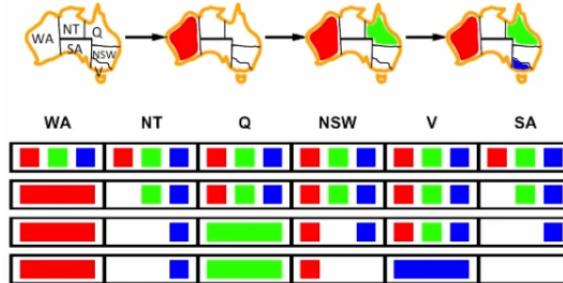
The idea is to keep track of domains for unassigned variables and cross off bad options. In forward checking we cross off values that violate a constraint when added to the existing assignment (look ahead).

forward checking propagates information from assigned to unassigned variables, but doesn't provide early detection for all failures. For example, (remember Australia map):

- Assume we chose to assign WA=Red
- Because NT, SA are neighbors, we remove Red from their domains

¹I am referring to the known Australia map example mentioned in the lecture notes

- Assume we pick next Q=Green
- Because NT, SA, NSW are neighbors, we remove Green from their domains
- At this point, forward checking thinks we are in good shape, but we are already doomed! *why?* Because NT, SA are neighbors and they both are left with only Blue in their domains!
- Assuming, next we choose V=Green, we cross off Green from NSW, SA, now SA is left with no colors, only then, we know we failed, so we backtrack.

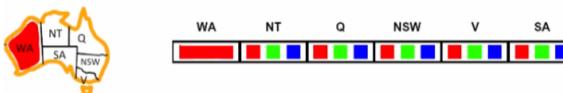


Def 4.17. Arc Consistency: Let $\gamma := \langle V, D, C \rangle$ be a **constraint network**, a variable $u \in V$ is **arc consistent** relative to another variable $v \in V$ if either $C_{uv} \notin C$, or for every value $d \in D_u$ there exist a value $d' \in D_v$ such that $(d, d') \in C_{uv}$. The **constraint network** γ is **arc consistent** if every variable $u \in V$ is **arc consistent** relative to every other variable $v \in V$.

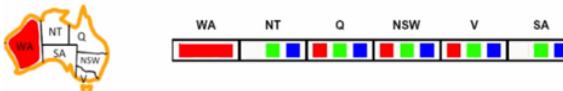
Note

Note that when we are checking some arc $x \rightarrow y$ and find it inconsistent, we remove values from D_x to make it consistent. When doing so, we need to check every other arc $z \rightarrow x$ (where the *tail* of the arc we checked is the *head* of other arcs) even if it was checked before (because now we have fewer options, it is not necessarily consistent anymore!)

Example:



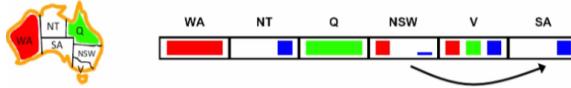
- Checking NT \rightarrow WA \rightsquigarrow removing Red from the domain of NT
- Checking SA \rightarrow WA \rightsquigarrow removing Red from the domain of SA
- All arcs are consistent now



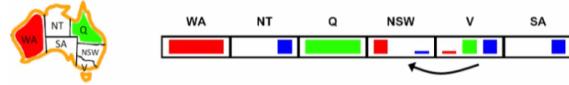
Assume we pick next Q=Green, and therefore remove Green from NT, NSW, SA:



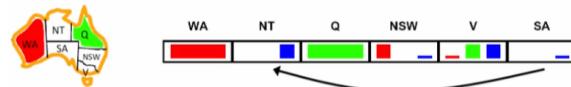
- Looking at V \rightarrow NSW \rightsquigarrow consistent
- Looking at SA \rightarrow NSW \rightsquigarrow consistent
- Looking at NSW \rightarrow SA \rightsquigarrow not consistent! If we choose NSW = Blue, nothing I can choose in SA that would not violate the constraint!
- We make NSW \rightarrow SA consistent by removing Blue from the domain of NSW



- Now, we check again the arc where NSW was the head.
- Looking at V \rightarrow NSW \rightsquigarrow not consistent



- Looking at SA \rightarrow NSW \rightsquigarrow consistent
- Continue checking arcs. Assume looking at SA \rightarrow NT \rightsquigarrow not consistent



- Now SA domain is empty, we know we failed, so we backtrack!
- Notice that we detect failure earlier than forward checking!

The pseudocode for the arc consistency algorithm (called AC-3) is shown in [Algorithm 2](#)

Algorithm 2 AC-3

```

1: function AC-3(csp)
2:   inputs: csp, a binary CSP with variables  $\{X_1, X_2, \dots, X_n\}$ 
3:   local variables: queue, a queue of arcs, initially all the arcs in csp
4:   while queue is not empty do
5:      $(X_i, X_j) \leftarrow \text{REMOVE-FIRST}(\text{queue})$ 
6:     if REMOVE-INCONSISTENT-VALUES $((X_i, X_j))$  then
7:       for each  $X_k$  in Neighbors $[X_i]$  do
8:         add  $(X_k, X_i)$  to queue
9:       end for
10:      end if
11:    end while
12:    return csp
13: end function
14: function REMOVE-INCONSISTENT-VALUES $((X_i, X_j))$ 
15:   removed  $\leftarrow$  false
16:   for each  $x$  in Domain $[X_i]$  do
17:     if no value  $y$  in Domain $[X_j]$  allows  $(x, y)$  to satisfy the constraint  $X_i \leftrightarrow X_j$  then
18:       delete  $x$  from Domain $[X_i]$ 
19:       removed  $\leftarrow$  true
20:     end if
21:   end for
22:   return removed
23: end function

```

- In the worst case, we have a fully connected **constraint network** of n variables, hence we will have a total of $n(n - 1)$ arcs.
- For one arc $x \rightarrow y$, if the number of values each variable can take is d , to make this arc consistent, we have one variable that has d possibilities (*the tail*) and the *head* too (another d possibilities), and we want to make sure for everything in the *tail* there is some value in the *head* that we can assign. That requires $d \cdot d$ checks in the worst case $= d^2$.
- Moreover, it is not enough to check each arc once. We enqueue an already dequeued arc whenever we eliminate a value from the domain of the arc's *head*. In the worst case, we might eliminate all the values of a variable, i.e. we put an arc back d times.

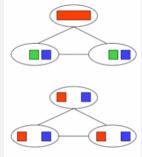
- Therefore, the total run time for AC-3 is $\mathcal{O}((n(n-1)) \cdot d^2 \cdot d) = \mathcal{O}(n^2d^3)$

Note

Notice that the run time \approx polynomial and yet detecting all possible future problems is NP-Hard because of backtracking. Arc consistency does not guarantee finding a solution. After enforcing arc consistency, we might have:

- one solution left
- multiple solutions left
- no solutions left (and not know it!)

Moreover, the algorithm still runs inside [backtracking search](#).



Def 4.18. Minimum Remaining Values: The [MRV heuristic](#) for [backtracking search](#) (*a.k.a* *Most Constrained Variable First*) selects the unassigned variable with the fewest [legal values](#) given the current partial [assignment](#) φ . Formally, it chooses the variable v that minimizes $|\{d \in D_v \mid \varphi \cup \{v \mapsto d\} \text{ is consistent}\}|$.

Note

[MRV](#) \mapsto we want to fail early! Hence, [MRV](#) ordering is also called fail-fast ordering.

Def 4.19. Least Constraining Value: Given a variable v , the [LCV heuristic](#) chooses the least constraining value for v , i.e. the one that rules out the fewest values in the remaining variables. For the current [partial assignment](#) φ and a chosen variable v , we pick a value $d \in D_v$ that minimizes $|d' \in D_u \mid u \notin \text{dom}(\varphi), C_{uv} \in C, \text{ and } (d', d) \notin C_{uv}|$

Def 4.20. Independent Subproblems: Assume we have independent connected components of a [constraint graph](#). We treat each component as a separate CSP since it has no constraints outside its variables.

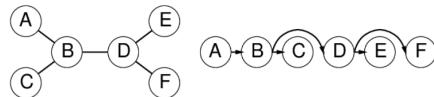
Remember, a naive solver (brute-force) solves a [discrete CSPs](#) with [domain size](#) d and n variables in $\mathcal{O}(d^n)$ (exponential in n). If that same problem has independent subproblems each with c variables, then we have $\frac{n}{c}$ subproblems where each one in the worst case is $\mathcal{O}(d^c)$. So the total time will be $\mathcal{O}(\frac{n}{c}d^c)$, that is, linear in n and exponential in c . That is very fast for small c .

Def 4.21. Decomposition: The process of decomposing a [constraint network](#) into [components](#).

Def 4.22. Tree-Structured CSP: We call a [CSP](#) [tree-structured](#) iff its [constraint graph](#) is [acyclic](#).

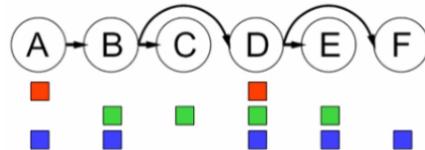
Theorem 4.1. A [Tree-Structured CSP](#) can be solved in $\mathcal{O}(nd^2)$

To solve a [Tree-Structured CSP](#), we choose a variable as [root](#) and order the variables from [root](#) to [leaves](#) such that every node's parent precedes it in the ordering:



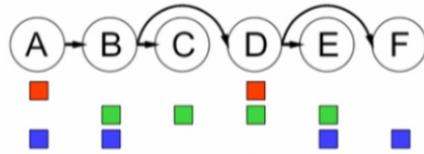
- Backward pass: For $i = n$ and down to 2, apply [Remove-Inconsistent-Values](#)(($\text{Parent}(X_i)$, X_i))
- Forward pass: For $i = 1$ and up to n , [assign](#) X_i [consistently](#) with $\text{Parent}(X_i)$

For example, consider the following domains:

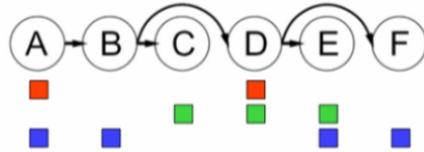


Backward Pass:

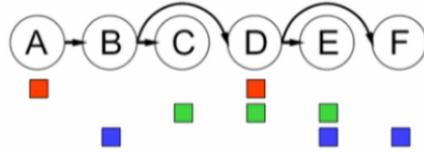
- Start with F , checking $D \rightarrow F \rightsquigarrow$ not consistent:



- Next is E , checking $D \rightarrow E \rightsquigarrow$ consistent.
- Next is D , checking $B \rightarrow D \rightsquigarrow$ consistent.
- Next is C , checking $B \rightarrow C \rightsquigarrow$ not consistent:



- Next is B , checking $A \rightarrow B \rightsquigarrow$ not consistent:



Forward Pass:

$\varphi(A) = \text{Red}$, $\varphi(B) = \text{Blue}$, $\varphi(C) = \text{Green}$, $\varphi(D) = \text{Green}$, $\varphi(E) = \text{Blue}$, $\varphi(F) = \text{Blue}$

Note

After the backward pass on a tree-structured CSP, every root-to-leaf arc becomes [consistent](#), and no arc ever needs to be enqueued again. The key reason is the direction in which consistency is enforced. Starting from the leaves and moving upward, each arc $x \rightarrow y$ is processed only after all of x 's children have been handled. When enforcing consistency on $x \rightarrow y$, we only remove values from the domain of the tail x . Since all arcs of the form $v \rightarrow x$ were already processed earlier, there will be no later step that removes values from the head y of any previously processed arc. In contrast to general AC algorithms, where pruning the head forces re-checking incoming arcs, the tree structure guarantees that once an arc's head has been finalized, it is never modified again. This is why no arc needs to be re-enqueued: domain reductions always flow upward toward the root, never back down.

Note

If root-to-leaf arcs are [consistent](#), the forward pass will not backtrack and will go straight to the solution!

Def 4.23. Conditioning: Instantiate a variable, prune its neighbors' [domains](#)

Def 4.24. Cutset conditioning: Instantiate in all ways a set of variables such that the remaining [constraint graph](#) is a [tree](#).

Note

A cutset of size c gives runtime $\mathcal{O}(d^c(n - c)d^2)$:

- Because we are left with a tree of size $n - c$, we have $\mathcal{O}((n - c)d^2)$
 - Because we have to look at all possible [assignments](#) of the cutset, we have $\mathcal{O}(d^c)$
- and that is very fast for small c !

5 Formal Systems

Def 5.1. Logical System: A **logical system** (or simply a **logic**) is a triple $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$, where

- \mathcal{L} is a **set** of **propositions**
- \mathcal{M} is a **set** of **models**,
- \models is a **relation** $\models \subseteq \mathcal{M} \times \mathcal{L}$ called the **satisfaction relation**. We read $\mathcal{M} \models A$ as \mathcal{M} **satisfies** A and correspondingly $\mathcal{M} \not\models A$ as \mathcal{M} **falsifies** A

Let $\langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system**, $M \in \mathcal{M}$ a model and $A \in \mathcal{L}$ a proposition. Then we say that A is

- **satisfied** by M iff $M \models A$
- **satisfiable** iff A is **satisfied** by some model
- **unsatisfiable** iff A is not **satisfiable**
- **falsified** by M iff $M \not\models A$
- **valid** or **unfalsifiable** (write $\models A$) iff A is **satisfied** by **every** model $M \in \mathcal{M}$
- **invalid** or **falsifiable** (write $\not\models A$) iff A is not **valid**

Def 5.2. Derivation Relation (\vdash): Let \mathcal{L} be a **formal language**. For any **set** of propositions $\mathcal{H} \subseteq \mathcal{L}$ (*called the context or hypotheses*) and any proposition $A \in \mathcal{L}$, we write $\mathcal{H} \vdash A$ to say that A is derivable from \mathcal{H} . We call a **relation** $\vdash \subseteq \mathcal{P}(\mathcal{L}) \times \mathcal{L}$ a **derivation relation** for \mathcal{L} , iff

- $\mathcal{H} \vdash A$, if $A \in \mathcal{H}$ (proof reflexive),
- $\mathcal{H} \vdash A$ and $(\mathcal{H}' \cup \{A\}) \vdash B$ imply $(\mathcal{H} \cup \mathcal{H}') \vdash B$ (proof transitive),
- $\mathcal{H} \vdash A$ and $\mathcal{H} \subseteq \mathcal{H}'$ imply $\mathcal{H}' \vdash A$ (monotonic admits weakening).

Def 5.3. Inference Rules: Let \mathcal{L} be a **formal language**, then an **inference rule** over \mathcal{L} is decidable $n + 1$ -ary **relation** on \mathcal{L} . Inference rules are traditionally written as:

$$\frac{A_1 \quad \dots \quad A_n}{C} \mathcal{N}$$

where A_1, \dots, A_n and C are schemata for words in \mathcal{L} and \mathcal{N} is a name. The A_i are called **assumptions** of \mathcal{N} , and C is called its **conclusion**.

Any $n + 1$ -tuple $\frac{a_1 \quad \dots \quad a_n}{c}$ in \mathcal{N} is called an **application** of \mathcal{N} and we say that we apply \mathcal{N} to a **set** M of words with $a_1, \dots, a_n \in M$ to obtain c .

Def 5.4. Axiom: An **inference rule** without **assumptions** is called an **axiom**

Def 5.5. Calculus: A **calculus** (or **inference system**) is a **formal language** \mathcal{L} equipped with a **set** \mathcal{C} of **inference rules** over \mathcal{L} .

Def 5.6. \mathcal{C} -derivation: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system**, and \mathcal{C} a **calculus** for \mathcal{L} , then a \mathcal{C} -derivation of a proposition $P \in \mathcal{L}$ from a **set** $\mathcal{H} \subseteq \mathcal{L}$ of hypotheses (write $\mathcal{H} \vdash_{\mathcal{C}} P$) is a sequence A_1, \dots, A_m of propositions where:

- $A_m = P$,
- for all $1 \leq i \leq m$, either $A_i \in \mathcal{H}$, or,
- there is an **inference rule** $\frac{A_{l_1} \quad \dots \quad A_{l_k}}{A_i} \mathcal{N}$ in \mathcal{C} with $l_j < i$ for all $j \leq k$

We can also see a \mathcal{C} -derivation as a **derivation tree**, where A_{l_j} are the children of the node A_i

Def 5.7. \mathcal{C} -refutation: Let \mathcal{C} be a **calculus**, then a **formula set** Φ is called \mathcal{C} -**refutable** if there is a \mathcal{C} -**refutation**, i.e. a \mathcal{C} -derivation of a **contradiction** from Φ . The act of finding a **refutation** for Φ is called **refuting** Φ

Def 5.8. Derivation System: We call $\langle \mathcal{L}, \mathcal{M}, \models, \vdash \rangle$ a **derivation system**, iff $\langle \mathcal{L}, \mathcal{M}, \models \rangle$ is a **logical system**, and \vdash a **derivation relation** for \mathcal{L} .

Assertion Let $\langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system**, and \mathcal{C} a **calculus**, then $\vdash_{\mathcal{C}}$ is a **derivation relation** and thus $\langle \mathcal{L}, \mathcal{M}, \models, \vdash_{\mathcal{C}} \rangle$ is a **derivation system**

Def 5.9. Formal System: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system**, and let \mathcal{C} be a **calculus** over the language \mathcal{L} . Then the pair $\langle \mathcal{S}, \mathcal{C} \rangle$ is called a **formal system**.

Note

Let \mathcal{C} be a calculus, then a \mathcal{C} -derivation $\emptyset \vdash_{\mathcal{C}} A$ is called a proof of A and if one exists (write $\vdash_{\mathcal{C}} A$) then A is called a \mathcal{C} -theorem.

Def 5.10. Admissible: An inference rule \mathcal{J} is called **admissible** in a calculus \mathcal{C} , if the extension of \mathcal{C} by \mathcal{J} does not yield new theorems

$$\frac{A_1 \quad \dots \quad A_n}{C} \mathcal{N}$$

Def 5.11. Derived Rules: An inference rule $\frac{A_1 \quad \dots \quad A_n}{C} \mathcal{N}$ is called **derived / derivable** in a calculus \mathcal{C} , if there is a \mathcal{C} -derivation $A_1, \dots, A_n \vdash_{\mathcal{C}} C$.

Note

Derivable inference rules are admissible, but not the other way around.

Theorem 5.1. It is not true that every admissible inference rule is derivable

Proof.

1. Construct an empty calculus \mathcal{C}_{\emptyset}
 2. Since we have no axioms and no inference rules, then the set of theorems is also empty $\text{Th}(\mathcal{C}_{\emptyset}) = \emptyset$
 3. Let \mathcal{J} be an arbitrary inference rule
- $$\frac{A_1 \quad \dots \quad A_n}{B} \mathcal{J}$$
4. Now we extend our empty calculus by this rule $\mathcal{C}_{\emptyset} \cup \mathcal{J}$
 5. Since we have no axioms, the rule \mathcal{J} has no input to operate on, therefore, the set of theorems stays empty $\text{Th}(\mathcal{C}_{\emptyset} \cup \mathcal{J}) = \emptyset$
 6. Thus, \mathcal{J} is admissible.
 7. Since \mathcal{C}_{\emptyset} has no rule and no axioms, it is impossible to construct steps from A_1, \dots, A_n to B
 8. Hence, \mathcal{J} is not derivable
 9. Since \mathcal{J} is admissible but not derived, the statement "every admissible inference rule is derivable" is False, hence, it is not true that every admissible inference rule is derivable.

□

6 Propositional Logic

Def 6.1. Propositional Logic: Propositional Logic (PL^0) is a logical system $\langle \mathcal{L}, \mathcal{M}, \models \rangle$ Where

- the formal language \mathcal{L} is defined as the well-formed formulae of propositional logic: $\text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$,
- the set \mathcal{M} of models is given by the set \mathcal{K}_0 of total functions $\varphi : \mathcal{V}_0 \rightarrow \mathcal{D}_0$ (i.e., propositional variable assignments),
- and $\varphi \models A$ iff $\mathcal{I}_\varphi(A) = T$ (a proposition is satisfiable by model φ if the interpretation of it -under that φ - is true)

Hence, propositional logic is a logical system $\langle \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0}), \mathcal{K}_0, \models \rangle$

Def 6.2. Formulae of PL^0 : The formulae of PL^0 are made up from

- propositional variables $\mathcal{V}_{\text{PL}^0}$ (or just \mathcal{V}_0): $\mathcal{V}_0 := \{P, Q, R, \dots\}$ (countably infinite)
- propositional signature Σ_{PL^0} (or just Σ_0): $\Sigma_0 := \{\top, \perp, \neg, \vee, \wedge, \Rightarrow, \Leftrightarrow, \dots\}$ (called connectives)

We define the set $\text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$ of well-formed propositional formulae (wffs) as:

- propositional variables
- logical constants \top and \perp
- negations $\neg A$
- conjunctions $A \wedge B$
- disjunctions $A \vee B$
- implications $A \Rightarrow B$, and
- equivalence (biimplications) $A \Leftrightarrow B$

where $A, B \in \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$ themselves.

Def 6.3. Grammar for PL^0 : The set of propositional formulae $\{A \mid A \in \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})\}$ is given by the following grammar:

$$\begin{aligned} X &::= P \mid Q \mid R \mid \dots \quad (\text{propositional variables}) \\ A &::= X \mid \top \mid \perp \mid \neg A \mid A \wedge A \mid A \vee A \mid A \Rightarrow A \mid A \Leftrightarrow A \end{aligned}$$

Def 6.4. Canonical Model: We call a logical system $\langle \mathcal{L}, \mathcal{M}, \models \rangle$ a single-model with canonical model M iff $\mathcal{M} = \{M\}$

Def 6.5. PL^0 Models: A model $\mathcal{M} := \langle \mathcal{D}_0, \mathcal{I} \rangle$ for PL^0 consists of

- the universe $\mathcal{D}_0 := \{T, F\}$ (truth values)
- the interpretation \mathcal{I} that assigns truth values to essential connectives
 1. $\mathcal{I}(\neg) : \mathcal{D}_0 \rightarrow \mathcal{D}_0; T \mapsto F, F \mapsto T$
 2. $\mathcal{I}(\wedge) : \mathcal{D}_0 \times \mathcal{D}_0 \rightarrow \mathcal{D}_0; \langle \alpha, \beta \rangle \mapsto T$, iff $\alpha = \beta = T$
 3. $\mathcal{I}(\top) = T$
 4. $\mathcal{I}(\perp) = F$

Note

PL^0 is a single-model logical system with canonical model $\langle \mathcal{D}_0, \mathcal{I} \rangle$

Def 6.6. Variable Assignment: PL^0 uses a total variable assignment $\varphi : \mathcal{V}_0 \rightarrow \mathcal{D}_0$ that assigns truth values to propositional variables.

Def 6.7. Value Function: PL^0 uses a value function $\mathcal{I}_\varphi : \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0}) \rightarrow \mathcal{D}_0$ that assigns truth values to PL^0 formulae. It is defined as follows:

- $\mathcal{I}_\varphi(P) = \varphi(P)$
- $\mathcal{I}_\varphi(\neg A) = \mathcal{I}(\neg)(\mathcal{I}_\varphi(A))$

- $\mathcal{I}_\varphi(A \wedge B) = \mathcal{I}(\wedge)(\mathcal{I}_\varphi(A), \mathcal{I}_\varphi(B))$

Note

Value Function Example: Compute $\mathcal{I}_\varphi(P \vee Q)$ under the assignment $\varphi := \{P \mapsto F, Q \mapsto T\}$

$$\begin{aligned}
 \mathcal{I}_\varphi(P \vee Q) &= \mathcal{I}_\varphi(\neg(\neg P \wedge \neg Q)) \\
 \mathcal{I}_\varphi(\neg P) &= \mathcal{I}(\neg)(\mathcal{I}_\varphi(P)) \\
 \mathcal{I}_\varphi(\neg Q) &= \mathcal{I}(\neg)(\mathcal{I}_\varphi(Q)) \\
 \mathcal{I}_\varphi(\neg P \wedge \neg Q) &= \mathcal{I}(\wedge)(\mathcal{I}_\varphi(\neg P), \mathcal{I}_\varphi(\neg Q)) \\
 \mathcal{I}_\varphi(P \vee Q) &= \mathcal{I}(\neg)(\mathcal{I}_\varphi(\neg P \wedge \neg Q)) \\
 &= \mathcal{I}(\neg)(\mathcal{I}(\wedge)(\mathcal{I}_\varphi(\neg P), \mathcal{I}_\varphi(\neg Q))) \\
 &= \mathcal{I}(\neg)(\mathcal{I}(\wedge)(\mathcal{I}(\neg)(\mathcal{I}_\varphi(P)), \mathcal{I}(\neg)(\mathcal{I}_\varphi(Q))))
 \end{aligned}$$

We know that

- $\mathcal{I}_\varphi(P) = \varphi(P) = F$, and
- $\mathcal{I}_\varphi(Q) = \varphi(Q) = T$

Hence:

$$\begin{aligned}
 &= \mathcal{I}(\neg)(\mathcal{I}(\wedge)(\mathcal{I}(\neg)(F), \mathcal{I}(\neg)(T))) \\
 &= \mathcal{I}(\neg)(\mathcal{I}(\wedge)(T, F)) \\
 &= \mathcal{I}(\neg)(F) \\
 &= T
 \end{aligned}$$

Def 6.8. Variable Occurrence: A function that maps a PL^0 formula to the set of variable occurred in that formula. It is defined as:

- $\text{Var}(P) = \{P\}$
- $\text{Var}(\top) = \emptyset$
- $\text{Var}(\perp) = \emptyset$
- $\text{Var}(\neg A) = \text{Var}(A)$
- $\text{Var}(A \circ B) = \text{Var}(A) \cup \text{Var}(B)$ where $\circ \in \{\wedge, \vee, \Rightarrow, \Leftrightarrow\}$

Def 6.9. Ground Formula: A PL^0 formula A is called **ground** iff $\text{Var}(A) = \emptyset$

Note

Alternative Notation: write $\llbracket A \rrbracket_\varphi$ for $\mathcal{I}_\varphi(A)$ (and $\llbracket A \rrbracket$ if A is ground)

Def 6.10. Equivalent: Two formulae A and B are called **equivalent**, iff $\mathcal{I}_\varphi(A) = \mathcal{I}_\varphi(B)$ for all variable assignments φ

Def 6.11. PL^0 Identities: Table 3 shows the identities in PL^0

Table 3: PL^0 Identities

Name	for \wedge	for \vee
Idempotence	$\varphi \wedge \varphi = \varphi$	$\varphi \vee \varphi = \varphi$
Identity	$\varphi \wedge \top = \varphi$	$\varphi \vee \perp = \varphi$
Absorption 1	$\varphi \wedge \perp = \perp$	$\varphi \vee \top = \top$
Commutativity	$\varphi \wedge \psi = \psi \wedge \varphi$	$\varphi \vee \psi = \psi \vee \varphi$
Associativity	$\varphi \wedge (\psi \wedge \theta) = (\varphi \wedge \psi) \wedge \theta$	$\varphi \vee (\psi \vee \theta) = (\varphi \vee \psi) \vee \theta$
Distributivity	$\varphi \wedge (\psi \vee \theta) = (\varphi \wedge \psi) \vee (\varphi \wedge \theta)$	$\varphi \vee (\psi \wedge \theta) = (\varphi \vee \psi) \wedge (\varphi \vee \theta)$
Absorption 2	$\varphi \wedge (\varphi \vee \theta) = \varphi$	$\varphi \vee (\varphi \wedge \theta) = \varphi$
De Morgan rule	$\neg(\varphi \wedge \psi) = \neg\varphi \vee \neg\psi$	$\neg(\varphi \vee \psi) = \neg\varphi \wedge \neg\psi$
double negation	$\neg\neg\varphi = \varphi$	
Definitions	$\varphi \Rightarrow \psi = \neg\varphi \vee \psi$	$\varphi \Leftrightarrow \psi = (\varphi \Rightarrow \psi) \wedge (\psi \Rightarrow \varphi)$

Let $\mathcal{M} := \langle \mathcal{D}_0, \mathcal{I} \rangle$ be our model, then we say that a formula A is

- **true under φ** in \mathcal{M} , iff $\mathcal{I}_\varphi(A) = T$, (write $\mathcal{M} \models^\varphi A$)
- **falsifies φ** in \mathcal{M} , iff $\mathcal{I}_\varphi(A) = F$, (write $\mathcal{M} \not\models^\varphi A$)
- **satisfiable in \mathcal{M}** , iff $\mathcal{I}_\varphi(A) = T$ for some **assignment** φ
- **valid in \mathcal{M}** , iff $\mathcal{M} \models^\varphi A$ for all **variable assignments** φ
- **falsifiable in \mathcal{M}** , iff $\mathcal{I}_\varphi(A) = F$ for some **assignment** φ , and
- **unsatisfiable in \mathcal{M}** , iff $\mathcal{I}_\varphi(A) = F$ for all **variable assignments** φ .

Note

Since PL^0 is a **single-model logical system**, we can omit the explicit reference to the **canonical model** and write $\varphi \models A$ to mean "A is true under φ ", recovering the notation from $\mathcal{M} \models^\varphi A$.

Def 6.12. Entailment: We say that A **entails** B (write $A \models B$), iff $\mathcal{I}_\varphi(B) = T$ for all φ with $\mathcal{I}_\varphi(A) = T$ (i.e. all **variable assignments**) that makes A true also make B true

Theorem 6.1. $A \models B \Rightarrow A \wedge C \models B \wedge C$

Proof.

1. Assume that $A \models B$ (\mathcal{H}_1), we want to show that for all φ that makes $A \wedge C$ true also make $B \wedge C$ true
2. Assume there is some φ that makes $A \wedge C$ true $\rightsquigarrow \mathcal{I}_\varphi(A \wedge C) = T$ (\mathcal{H}_2)
3. This means that $\mathcal{I}_\varphi(A) = \mathcal{I}_\varphi(C) = T$
4. Given \mathcal{H}_1 we now know that our φ also make B true $\rightsquigarrow \mathcal{I}_\varphi(B) = T$
5. From 3 and 4 and by the definition of conjunction: $\mathcal{I}_\varphi(B \wedge C) = T$

□

Def 6.13. Soundness: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system** and $\mathcal{H} \subseteq \mathcal{L}$ a **set** of hypotheses, then we call a **calculus** \mathcal{C} over \mathcal{L} **sound** (correct), iff $\mathcal{H} \models A$ whenever $\mathcal{H} \vdash_{\mathcal{C}} A$

Def 6.14. Completeness: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a **logical system** and $\mathcal{H} \subseteq \mathcal{L}$ a **set** of hypotheses, then we call a **calculus** \mathcal{C} over \mathcal{L} **complete**, iff $\mathcal{H} \vdash_{\mathcal{C}} A$ whenever $\mathcal{H} \models A$

Def 6.15. Hilbert Calculus: The Hilbert calculus \mathcal{H}^0 is a **calculus** that consists of the following **inference rules**:

$$\begin{array}{c} \frac{}{P \Rightarrow (Q \Rightarrow P)} K \quad \frac{(P \Rightarrow (Q \Rightarrow R)) \Rightarrow ((P \Rightarrow Q) \Rightarrow (P \Rightarrow R))}{(P \Rightarrow (Q \Rightarrow R)) \Rightarrow ((P \Rightarrow Q) \Rightarrow (P \Rightarrow R))} S \\ \\ \frac{A \Rightarrow B \quad A}{B} \text{ MP} \quad \frac{A}{[B/X](A)} \text{ Subst} \end{array}$$

Note

Subst inference rule is **admissible** but not **derivable**

Def 6.16. Hilbert Formal System: Using **propositional logic** and the **Hilbert Calculus**, we can build a simple **formal system**:

$$\langle \underbrace{\langle \mathcal{L}, \mathcal{M}, \models \rangle}_{\text{propositional logic}}, \underbrace{\mathcal{H}^0}_{\text{Hilbert Calculus}} \rangle$$

Example: $C \Rightarrow C$ is a \mathcal{H}^0 and here is its **proof**:

Proof. We show that $\emptyset \vdash_{\mathcal{H}^0} C \Rightarrow C$

1. **axiom** S gives us:

$$(P \Rightarrow (Q \Rightarrow R)) \Rightarrow ((P \Rightarrow Q) \Rightarrow (P \Rightarrow R))$$

2. We apply Subst with $[C/P], [C \Rightarrow C/Q], [C/R]$, we get:

$$(C \Rightarrow ((C \Rightarrow C) \Rightarrow C)) \Rightarrow ((C \Rightarrow (C \Rightarrow C)) \Rightarrow (C \Rightarrow C))$$

3. **axiom K** gives us:

$$P \Rightarrow (Q \Rightarrow P)$$

4. We apply Subst with $[C/P], [C \Rightarrow C/Q]$, we get:

$$C \Rightarrow ((C \Rightarrow C) \Rightarrow C)$$

5. We use MP on 4 and 2, we get:

$$(C \Rightarrow (C \Rightarrow C)) \Rightarrow (C \Rightarrow C)$$

6. **axiom K** gives us:

$$P \Rightarrow (Q \Rightarrow P)$$

7. We apply Subst with $[C/P], [C/Q]$, we get:

$$C \Rightarrow (C \Rightarrow C)$$

8. We apply MP on 7 and 5, we get:

$$C \Rightarrow C$$

□

Def 6.17. \mathcal{ND}_0 : The propositional natural deduction calculus \mathcal{ND}_0 has inference rules for the introduction and elimination of connectives. \mathcal{ND}_0 rules are shown in figure 1

$\frac{A \quad B}{A \wedge B} \wedge I$	$\frac{A \wedge B}{A} \wedge E_l$	$\frac{A \wedge B}{B} \wedge E_r$
$\frac{\begin{array}{c} [A]^1 \\ \vdots \\ B \end{array}}{A \Rightarrow B} \Rightarrow I^1$		$\frac{A \Rightarrow B \quad A}{B} \Rightarrow E$
$\frac{A \vee \neg A}{A \vee \neg A} \mathcal{TND}$		
$\frac{A}{A \vee B} \vee I_l$		$\frac{B}{A \vee B} \vee I_r$
	$\frac{\begin{array}{c} [A]^1 \quad [B]^1 \\ \vdots \quad \vdots \\ C \quad C \end{array}}{A \vee B \quad C \quad C} \vee E^1$	
$\frac{\begin{array}{c} [A]^1 \quad [A]^1 \\ \vdots \quad \vdots \\ C \quad \neg C \end{array}}{\neg A} \neg I^1$		$\frac{\neg \neg A}{A} \neg E$
$\frac{\neg A \quad A}{\perp} \perp I$		$\frac{\perp}{A} \perp E$

Figure 1: Propositional Natural Deduction Rules

Note

Rules below the dashed line “- -” are all derived rules from the original set above that line

Def 6.18. \mathcal{ND}_0 Derivation Tree: Given a set $\mathcal{H} \subseteq \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$ of assumptions and a conclusion C , we write $\mathcal{H} \vdash_{\mathcal{ND}_0} C$, iff there is an \mathcal{ND}_0 derivation tree whose leaves are in \mathcal{H}

Def 6.19. Hypothetical Reasoning: Notice that the rule $(\Rightarrow I)$ proves $A \Rightarrow B$ by exhibiting an \mathcal{ND}_0 derivation D (*depicted by the three vertical dots*) of B from a local hypothesis A . $(\Rightarrow I)$ then **discharges** the local hypothesis (*get rid of* A , which can only be used in D) and **concludes** $A \Rightarrow B$. This mode of reasoning is called **hypothetical reasoning** (*proof by local hypothesis*).

Note

The $\mathcal{TN}\mathcal{D}$ axiom in the \mathcal{ND}_0 calculus is called *the law/principle of excluded middle/third* (in latin *tertium non datur*) is only acceptable in **classical logic**, intuitionistic/constructive logic/mathematics does not affirm that law. (That applies for the derived rule $(\neg E)$ too)

$$\begin{array}{c}
 \frac{}{\Gamma, A \vdash A} \text{ Ax} \quad \frac{\Gamma \vdash B}{\Gamma, A \vdash B} \text{ weaken} \quad \frac{}{\Gamma \vdash A \vee \neg A} \mathcal{TN}\mathcal{D} \\
 \\
 \frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \wedge B} \wedge I \quad \frac{\Gamma \vdash A \wedge B}{\Gamma \vdash A} \wedge E_l \quad \frac{\Gamma \vdash A \wedge B}{\Gamma \vdash B} \wedge E_r \\
 \\
 \frac{\Gamma \vdash A}{\Gamma \vdash A \vee B} \vee I_l \quad \frac{\Gamma \vdash A \vee B \quad \Gamma, A \vdash C \quad \Gamma, B \vdash C}{\Gamma \vdash C} \vee E \quad \frac{\Gamma \vdash B}{\Gamma \vdash A \vee B} \vee I_r \\
 \\
 \frac{\Gamma, A \vdash B}{\Gamma \vdash A \Rightarrow B} \Rightarrow I \quad \frac{\Gamma \vdash A \Rightarrow B \quad \Gamma \vdash A}{\Gamma \vdash B} \Rightarrow E \\
 \\
 \frac{\Gamma, A \vdash \perp}{\Gamma \vdash \neg A} \neg I \quad \frac{\Gamma \vdash \neg \neg A}{\Gamma \vdash A} \neg E \\
 \\
 \frac{\Gamma \vdash \neg A \quad \Gamma \vdash A}{\Gamma \vdash \perp} \perp I \quad \frac{\Gamma \vdash \perp}{\Gamma \vdash A} \perp E
 \end{array}$$

Figure 2: Propositional Sequent Style Natural Deduction Calculus

Note

The sequent style of \mathcal{ND}_0 calculus (\mathcal{ND}_\vdash^0) is shown in figure 2

Example: Figures 3 to 6 show different \mathcal{ND}_0 proof styles for the following propositional formula:

$$(A \vee B) \wedge (A \Rightarrow C) \wedge (B \Rightarrow C) \Rightarrow C$$

Let $\Gamma = (A \vee B) \wedge ((A \Rightarrow C) \wedge (B \Rightarrow C))$.

$$\frac{\frac{\frac{\frac{\frac{\frac{\frac{\Gamma \vdash \Gamma}{\Gamma, A \vdash \Gamma} \text{ Ax}}{\Gamma, A \vdash (A \Rightarrow C) \wedge (B \Rightarrow C)} \wedge E_r}{\frac{\Gamma, A \vdash A \Rightarrow C}{\Gamma, A \vdash C} \wedge E_l}{\frac{\Gamma, A \vdash A}{\Gamma, A \vdash A} \Rightarrow E} \Rightarrow E}{\frac{\frac{\frac{\frac{\Gamma \vdash \Gamma}{\Gamma, B \vdash \Gamma} \text{ Ax}}{\Gamma, B \vdash (A \Rightarrow C) \wedge (B \Rightarrow C)} \wedge E_r}{\frac{\Gamma, B \vdash B \Rightarrow C}{\Gamma, B \vdash C} \wedge E_r}{\frac{\Gamma, B \vdash B}{\Gamma, B \vdash B} \Rightarrow E} \Rightarrow E}{\frac{\Gamma \vdash C}{\vdash \Gamma \Rightarrow C} \Rightarrow I}}{\Gamma \vdash A \vee B} \wedge E_l$$

Figure 3: Gentzen Sequent Style Proof

Let $\Gamma = (A \vee B) \wedge ((A \Rightarrow C) \wedge (B \Rightarrow C))$.

$$\frac{\frac{\frac{\frac{\frac{\frac{\frac{[\Gamma]^1}{(A \Rightarrow C) \wedge (B \Rightarrow C)} \wedge E_r}{\frac{[\Gamma]^1}{A \Rightarrow C} \wedge E_l}{\frac{[A]^2}{C} \Rightarrow E}}{\frac{[\Gamma]^1}{B \Rightarrow C} \wedge E_r}{\frac{[B]^2}{C} \vee E^2}}{\frac{C}{\Gamma \Rightarrow C} \Rightarrow I^1}}{\Gamma \vdash A \vee B} \wedge E_l$$

Figure 4: Gentzen-Prawitz Style Proof

Step	Formula	Rule Applied
(1)	$(A \vee B) \wedge (A \Rightarrow C) \wedge (B \Rightarrow C)$	Assumption
(2)	$A \vee B$	$\wedge E_l$ (on 1)
(3)	$(A \Rightarrow C) \wedge (B \Rightarrow C)$	$\wedge E_r$ (on 1)
(4)	$A \Rightarrow C$	$\wedge E_l$ (on 3)
(5)	$B \Rightarrow C$	$\wedge E_r$ (on 3)
(6)	A	Assumption (Case 1)
(7)	C	$\Rightarrow E$ (on 4 and 6)
(8)	B	Assumption (Case 2)
(9)	C	$\Rightarrow E$ (on 5 and 8)
(10)	C	$\vee E$ (on 2, 7 and 9) <i>Discharges assumptions 6 & 8</i>
(11)	$((A \vee B) \wedge (A \Rightarrow C) \wedge (B \Rightarrow C)) \Rightarrow C$	$\Rightarrow I$ (on 1 and 10) <i>Discharges assumption 1</i>

Figure 5: Linearized (Tabular) Style Proof

1	$(A \vee B) \wedge ((A \Rightarrow C) \wedge (B \Rightarrow C))$	Assumption
2	$A \vee B$	$\wedge E_l$ (on 1)
3	$(A \Rightarrow C) \wedge (B \Rightarrow C)$	$\wedge E_r$ (on 1)
4	$A \Rightarrow C$	$\wedge E_l$ (on 3)
5	$B \Rightarrow C$	$\wedge E_r$ (on 3)
6	$\frac{}{A}$	Assumption
7	$\frac{}{C}$	$\Rightarrow E$ (on 4, 6)
8	$\frac{}{B}$	Assumption
9	$\frac{}{C}$	$\Rightarrow E$ (on 5, 8)
10	C	$\vee E$ (on 2, 7, 9)
11	$((A \vee B) \wedge ((A \Rightarrow C) \wedge (B \Rightarrow C))) \Rightarrow C$	$\Rightarrow I$ (on 1–10)

Figure 6: Fitch Style Proof

Def 6.20. First-Order Signature: A First-Order (Logic) Signature (FOL Signature) is a tuple $\Sigma := \langle \Sigma^f, \Sigma^p \rangle$ where:

- $\Sigma^f := \bigcup_{k \in \mathbb{N}} \Sigma_k^f$ of **function constants** (or **terms**), where members of Σ_k^f denote the k -ary **functions** on **individuals**
- $\Sigma^p := \bigcup_{k \in \mathbb{N}} \Sigma_k^p$ of **predicate constants**, where member of Σ_k^p denote k -ary **relations** among individuals
- Σ_k^f and Σ_k^p are **pairwise disjoint, countable sets** of symbols for each $k \in \mathbb{N}$.
- A 0-ary **function constant** refers to a single **individual**, therefore, we call it an **individual constant**

Def 6.21. Predicate Logic Without Quantifiers PL^{nq} : Given a **FOL Signature** Σ , the **formulae** of PL^{nq} are given by the following **grammar**:

$$\begin{aligned} f^k &\in \Sigma_k^f \\ p^k &\in \Sigma_p^f \\ t &:= f^0 \mid f^k(t_1, \dots, t_k) \\ A &:= p^k(t_1, \dots, t_k) \mid \neg A \mid A \wedge A \end{aligned}$$

Def 6.22. Well-Formed Terms: We denote the **set** of all well-formed **terms** over a **FOL Signature** Σ with $wff_t(\Sigma)$, and the **closed** ones with $cwff_t(\Sigma)$

Def 6.23. Well-Formed Formulae: We denote the **set** of all well-formed **formulae** over a **FOL Signature** Σ with $wff_o(\Sigma)$, and the **closed** ones with $cwff_o(\Sigma)$

Note

The Greek letter ι (read *iota*) stands for **individuals** (objects), however, \circ (read *omicron*) refers to **propositions** that can be true or false

Def 6.24. PL^{nq} Universe: PL^{nq} uses the universe $\mathcal{D}_{PL^{nq}} := \mathcal{D}_0 \cup \mathcal{D}_\iota$ where $\mathcal{D}_0 = \{T, F\}$ is the **set** of truth values and $\mathcal{D}_\iota \neq \emptyset$ is a non-empty **set** of **individuals**

Def 6.25. Interpretation in PL^{nq} : The interpretation function in PL^{nq} assigns values to **constants**:

1. We use the **interpretation** from PL^0

- $\mathcal{I}(\neg) : \mathcal{D}_0 \rightarrow \mathcal{D}_0; T \mapsto F, F \mapsto T$
- $\mathcal{I}(\wedge) : \mathcal{D}_0 \times \mathcal{D}_0 \rightarrow \mathcal{D}_0; \langle \alpha, \beta \rangle \mapsto T, \text{ iff } \alpha = \beta = T$
- $\mathcal{I}(T) = T$
- $\mathcal{I}(\perp) = F$

2. We interpret **individual constants** as **individuals**: $\mathcal{I} : \Sigma_0^f \rightarrow \mathcal{D}_\iota$

3. We interpret **function constants** as **functions**: $\mathcal{I} : \Sigma_{k \neq 0}^f \rightarrow \mathcal{D}_\iota^{k \neq 0} \rightarrow \mathcal{D}_\iota$

4. We interpret predicate constants as relations: $\mathcal{I} : \Sigma_k^p \rightarrow \mathcal{P}(\mathcal{D}_\iota^k)$

Note

This definition naturally includes propositions as a special case. By defining $\mathcal{I} : \Sigma_k^p \rightarrow \mathcal{P}(\mathcal{D}_\iota^k)$, we see that for $k = 0$:

$$\mathcal{D}_\iota^0 = \{\langle \rangle\} \implies \mathcal{P}(\mathcal{D}_\iota^0) = \{\emptyset, \{\langle \rangle\}\} \cong \{F, T\}$$

Thus, a 0-ary predicate constant is interpreted as a truth value (a proposition), just like in propositional logic.

Def 6.26. Value Function: The value function assigns values to formulae:

1. $\mathcal{I}(f(A_1, \dots, A_k)) := \mathcal{I}(f)(\mathcal{I}(A_1), \dots, \mathcal{I}(A_k))$
2. $\mathcal{I}(p(A_1, \dots, A_k)) := T$, iff $\langle \mathcal{I}(A_1), \dots, \mathcal{I}(A_k) \rangle \in \mathcal{I}(p)$
3. and Just as in PL^0 :

- $\mathcal{I}(\neg A) := \mathcal{I}(\neg)(\mathcal{I}(A))$
- $\mathcal{I}(A \wedge B) := \mathcal{I}(\wedge)(\mathcal{I}(A), \mathcal{I}(B))$

Theorem 6.2. PL^{nq} is isomorphic to PL^0

Theorem 6.3. Unsatisfiability Theorem. $\mathcal{H} \models A \Leftrightarrow \mathcal{H} \cup \{\neg A\}$ is unsatisfiable.

Proof.

1. Assume $\mathcal{H} \models A$
 - For any φ with $\varphi \models H$ we have $\varphi \models A$ and thus $\varphi \not\models (\neg A)$
2. Assume $\mathcal{H} \cup \{\neg A\}$ is unsatisfiable
 - For any φ with $\varphi \models \mathcal{H}$ we have $\varphi \not\models (\neg A)$ and thus $\varphi \models A$

□

7 Machine-Oriented Calculi for Propositional Logic

Note

From [Theorem 6.3](#), we observe that [entailment](#) can be tested via [satisfiability](#)

Def 7.1. Theorem Proving: Given a [formal system](#) $\langle \mathcal{S}, \mathcal{C} \rangle$, where \mathcal{C} is a [calculus](#) and $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ is a [logical system](#), the task of [theorem proving](#) is the task of determining whether $\mathcal{H} \vdash_{\mathcal{C}} C$ for a [conjecture](#) $C \in \mathcal{L}$ and hypotheses $\mathcal{H} \subseteq \mathcal{L}$

Def 7.2. Automated Theorem Proving: ATP is the automation of [theorem proving](#).

Def 7.3. Test Calculus: For a given [conjecture](#) A and [hypotheses](#) \mathcal{H} , a [test calculus](#) \mathcal{T} tries to derive a [refutation](#) $\mathcal{H}, \neg A \vdash_{\mathcal{T}} \perp$ instead of $\mathcal{H} \vdash A$, where $\neg A$ is [unsatisfiable](#) iff A is [valid](#) and \perp an [unsatisfiable proposition](#).

Def 7.4. Atomic Formulae: A [formula](#) is called **atomic** (or an **atom**) if it does not contain logical constants, otherwise, **complex**

Def 7.5. Labeled Formula: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a [logical system](#), $A \in \mathcal{L}$ a formula, L a [label set](#), and $\alpha \in L$ a [label](#), then we call a [pair](#) $\langle A, \alpha \rangle$ a [labeled formula](#) and write it as A^α . For a [set](#) Φ of [propositions](#) we use $\Phi^\alpha := \{A^\alpha \mid A \in \Phi\}$

Note

If the [label set](#) is $\mathcal{D}_0 := \{T, F\}$, we call a [labeled formula](#) A^T **positive** and A^F **negative**

Note

Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a [logical system](#), and A^α a [labeled formula](#). Then we say that $M \in \mathcal{M}$ **satisfies** A^α (write $M \models A^\alpha$), iff $\alpha = T$ and $M \models A$ or $\alpha = F$ and $M \not\models A$

Def 7.6. Literal: Let $\mathcal{S} := \langle \mathcal{L}, \mathcal{M}, \models \rangle$ be a [logical system](#), $A \in \mathcal{L}$ is an [atomic formula](#), and $\alpha \in \{T, F\}$, then we call the [labeled formula](#) A^α a [literal](#).

Def 7.7. Opposite Literal: For a [literal](#) A^α , we call the [literal](#) A^β with $\alpha \neq \beta$ the [opposite literal](#).

Def 7.8. CNF: A [formula](#) is in [conjunctive normal form](#) (CNF) if it is \top or a conjunction of disjunctions of [literals](#), i.e. if it is of the form:

$$\bigwedge_{i=1}^n \bigvee_{j=1}^{m_i} l_{ij} := \underbrace{(l_{1,1} \vee \dots \vee l_{1,m_1})}_{\text{Clause } i=1 \text{ has } m_1 \text{ literals}} \wedge \underbrace{(l_{2,1} \vee \dots \vee l_{2,m_2})}_{\text{Clause } i=2 \text{ has } m_2 \text{ literals}} \wedge \dots \wedge \underbrace{(l_{n,1} \vee \dots \vee l_{n,m_n})}_{\text{Clause } i=n \text{ has } m_n \text{ literals}}$$

There are n total clauses

Def 7.9. DNF: A [formula](#) is in [disjunctive normal form](#) (DNF) if it is \perp or a disjunction of conjunctions of [literals](#), i.e. if it is of the form:

$$\bigvee_{i=1}^n \bigwedge_{j=1}^{m_i} l_{ij} := \underbrace{(l_{1,1} \wedge \dots \wedge l_{1,m_1})}_{\text{Term } i=1 \text{ has } m_1 \text{ literals}} \vee \underbrace{(l_{2,1} \wedge \dots \wedge l_{2,m_2})}_{\text{Term } i=2 \text{ has } m_2 \text{ literals}} \vee \dots \vee \underbrace{(l_{n,1} \wedge \dots \wedge l_{n,m_n})}_{\text{Term } i=n \text{ has } m_n \text{ literals}}$$

There are n total terms

Note

\top is in CNF because it represents the **empty conjunction**. (The semantic identity for conjunction is T , so we use the constant \top where $\mathcal{I}(\top) = T$). \perp is in DNF because it represents the **empty disjunction**. (The semantic identity for disjunction is F , so we use the constant \perp where $\mathcal{I}(\perp) = F$).

Def 7.10. Tableau Calculus: A [tableau calculus](#) is a [test calculus](#) that analyzes a [labeled formula](#) in a [tree](#) to determine [satisfiability](#), its branches correspond to [valuations](#) ([models](#))

Def 7.11. Saturated Tableau: We call a tableau **saturated** iff no application of a [rule](#) adds new material to any branch.

Def 7.12. Closed and Open Branches: A tableau branch is **closed** if it ends with \perp . Otherwise, the branch is **open**.

Note

We sometimes decorate **open** branches with a \square symbol to visually indicate they are finished and non-contradictory.

Def 7.13. Closed Tableau: A tableau is **closed** iff every one of its branches is **closed**. Otherwise, the tableau is **open**.

Note

It is crucial to distinguish between the **outcome** of a proof and the **completion** of the process:

- **Closed vs. Open:** This refers to the *logical status*. A tableau is **closed** if a contradiction is found on **every** branch. It is **open** if at least one branch remains consistent.
- **Saturated vs. Unsaturated:** This refers to the *construction status*. A tableau is **saturated** if no more rules can be applied to any branch.

Note: A **closed** tableau is rarely **saturated**. Once a specific branch closes, we stop applying rules to **that branch** for efficiency, even if formulas on that branch could still be expanded.

Note

Open branches in a **saturated** tableau yield **satisfying assignments**

Def 7.14. \mathcal{T}_0 : The Propositional Tableau Calculus \mathcal{T}_0 has the **inference rules** shown in figure 7

$\frac{(A \wedge B)^T}{\begin{array}{c} A^T \\ B^T \end{array}} \mathcal{T}_0 \wedge$	$\frac{(A \wedge B)^F}{A^F \mid B^F} \mathcal{T}_0 \vee$
$\frac{(\neg A)^T}{A^F} \mathcal{T}_0 \neg^T$	$\frac{(\neg A)^F}{A^T} \mathcal{T}_0 \neg^F$
$\frac{\begin{array}{c} A^\alpha \\ \vdots \\ A^\beta \quad (\alpha \neq \beta) \end{array}}{\perp} \mathcal{T}_0 \perp$	
$\frac{(A \Rightarrow B)^T}{A^F \mid B^T}$	$\frac{(A \Rightarrow B)^F}{\begin{array}{c} A^T \\ B^F \end{array}}$
$\frac{(A \vee B)^T}{A^T \mid B^T}$	$\frac{(A \vee B)^F}{\begin{array}{c} A^F \\ B^F \end{array}}$
$\frac{(A \iff B)^T}{\begin{array}{c} A^T \mid A^F \\ B^T \mid B^F \end{array}}$	$\frac{(A \iff B)^F}{\begin{array}{c} A^T \mid A^F \\ B^F \mid B^T \end{array}}$

Figure 7: Propositional Tableau Calculus \mathcal{T}_0

Def 7.15. \mathcal{T}_0 -Theorem: A is a \mathcal{T}_0 -theorem ($\vdash_{\mathcal{T}_0} A$), iff there is a **closed tableau** with A^F at the **root**.

Def 7.16. : A **labeled formula** A^α is **valid under** φ , iff $\mathcal{I}_\varphi(A) = \alpha$

Def 7.17. Satisfiable Tableau: A tableau \mathcal{T} is **satisfiable**, iff there is a satisfiable branch \mathcal{B} in \mathcal{T} , i.e. if the **set** of

formulae on \mathcal{B} is **satisfiable**.

Theorem 7.1. \mathcal{T}_0 is **sound**, i.e. $\Phi \subseteq \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$ is **valid** if there is a **closed tableau** \mathcal{T} for Φ^F .

Theorem 7.2. \mathcal{T}_0 is **complete**, i.e. if $\Phi \subseteq \text{wff}_0(\Sigma_{\text{PL}^0}, \mathcal{V}_{\text{PL}^0})$ is **valid**, then there is a **closed tableau** \mathcal{T} for Φ^F .

Lemma 7.3. \mathcal{T}_0 terminates, i.e. every \mathcal{T}_0 tableau becomes **saturated** after **finitely** many rule applications.

Corollary 7.4. \mathcal{T}_0 induces a decision procedure for **validity** in PL^0 .

Proof.

- By Lemma 7.3, it is decidable whether $\vdash_{\mathcal{T}_0} A$
- By Theorem 7.1 and Theorem 7.2, $\vdash_{\mathcal{T}_0} A$ iff A is **valid**

□

Example: Figure 8 shows a \mathcal{T}_0 proof of the formula $(A \vee B) \wedge (A \Rightarrow C) \wedge (B \Rightarrow C) \Rightarrow C$

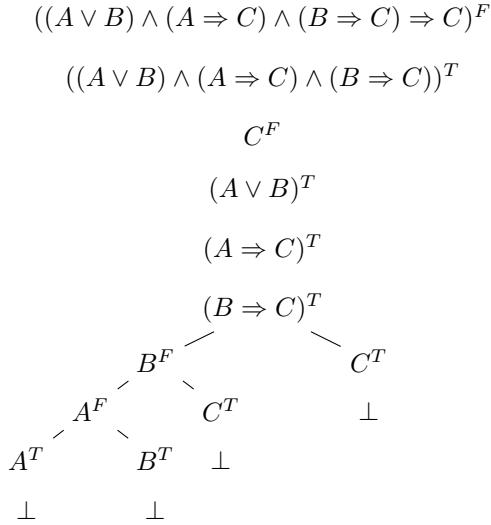


Figure 8: \mathcal{T}_0 Proof Example

Def 7.18. Clause: A **clause** is a disjunction $l_1^{\alpha_1} \vee \dots \vee l_n^{\alpha_n}$ of **literals**. We use \square for the "empty" disjunction (no disjuncts) and call it the **empty clause**. A clause with exactly one **literal** is called a **unit clause**.

Def 7.19. Clause Set: We often write a **clause set** $\{C_1, \dots, C_n\}$ as $C_1; \dots; C_n$, and write $S; T$ for the **union** of the clause sets S and T , and $S; C$ for the extension of S by a **clause** C .

Def 7.20. \mathcal{R}_0 : The propositional resolution calculus \mathcal{R}_0 operates on **clause sets** via a single **inference rule**:

$$\frac{P^T \vee A \quad P^F \vee B}{A \vee B} \mathcal{R}_0$$

This rule allows to add the **resolvent** $(A \vee B)$ to a **clause set** which contains the two **clauses** $P^T \vee A$ and $P^F \vee B$. The **literals** P^T and P^F are called **cut literals**.

Note

Modus Ponens can be viewed as a specific instance of the \mathcal{R}_0 rule. Given the premises $P \rightarrow Q$ and P , we first convert the implication to its clausal form $\neg P \vee Q$. Mapping this to the \mathcal{R}_0 definition:

- Let the first clause be $P^T \vee \perp$.
- Let the second clause be $P^F \vee Q$.

The application of the rule then results in:

$$\frac{P^T \vee \perp \quad P^F \vee Q}{Q} \mathcal{R}_0$$

which simplifies to the standard Modus Ponens conclusion Q .

Def 7.21. Resolution Refutation: Let S be a clause set, then we call an \mathcal{R}_0 -derivation of the empty clause \square from S \mathcal{R}_0 -refutation and write $\mathcal{D} : S \vdash_{\mathcal{R}_0} \square$.

Def 7.22. CNF Calculus: \mathcal{R}_0 operates only on clause sets (CNF), to transform formulae into CNF we use the propositional CNF calculus (CNF_0) which is shown in figure 9.

$\frac{C \vee (A \vee B)^T}{C \vee A^T \vee B^T} \vee^T$	$\frac{C \vee (A \vee B)^F}{(C \vee A^F) \wedge (C \vee B^F)} \vee^F$
$\frac{C \vee \neg A^T}{C \vee A^F} \neg^T$	$\frac{C \vee \neg A^F}{C \vee A^T} \neg^F$

$\frac{C \vee (A \Rightarrow B)^T}{C \vee A^F \vee B^T} \Rightarrow^T$	$\frac{C \vee (A \Rightarrow B)^F}{(C \vee A^T) \wedge (C \vee B^F)} \Rightarrow^F$
$\frac{C \vee (A \wedge B)^T}{(C \vee A^T) \wedge (C \vee B^T)} \wedge^T$	$\frac{C \vee (A \wedge B)^F}{C \vee A^F \vee B^F} \wedge^F$

Figure 9: Propositional CNF Calculus

Note

We write $\text{CNF}_0(A^\alpha)$ for the set of all clauses derivable from A^α via CNF_0

Example: We want to prove using \mathcal{R}_0 .

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

We label it with F , then we transform it to CNF using CNF_0 :

$$\begin{aligned} & \frac{((p \Rightarrow (q \Rightarrow r)) \Rightarrow ((p \Rightarrow q) \Rightarrow (p \Rightarrow r)))^F}{(p \Rightarrow (q \Rightarrow r))^T \wedge ((p \Rightarrow q) \Rightarrow (p \Rightarrow r))^F} \Rightarrow^F \\ & \frac{(p \Rightarrow (q \Rightarrow r))^T \wedge (p \Rightarrow q)^T \wedge (p \Rightarrow r)^F}{(p \Rightarrow (q \Rightarrow r))^T \wedge (p \Rightarrow q)^T \wedge (p \Rightarrow r)^F} \Rightarrow^F \\ & \frac{(p \Rightarrow (q \Rightarrow r))^T \wedge (p \Rightarrow q)^T \wedge p^T \wedge r^F}{(p \Rightarrow (q \Rightarrow r))^T \wedge (p \Rightarrow q)^T \wedge p^T \wedge r^F} \Rightarrow^F \end{aligned}$$

Then, expanding the T terms:

$$\begin{aligned} & \frac{(p \Rightarrow (q \Rightarrow r))^T \wedge (p \Rightarrow q)^T \wedge p^T \wedge r^F}{(p \Rightarrow (q \Rightarrow r))^T \wedge (p^F \vee q^T) \wedge p^T \wedge r^F} \Rightarrow^T \\ & \frac{(p^F \vee (q \Rightarrow r)^T) \wedge (p^F \vee q^T) \wedge p^T \wedge r^F}{(p^F \vee q^F \vee r^T) \wedge (p^F \vee q^T) \wedge p^T \wedge r^F} \Rightarrow^T \\ & \frac{(p^F \vee q^F \vee r^T) \wedge (p^F \vee q^T) \wedge p^T \wedge r^F}{(p^F \vee q^F \vee r^T) \wedge (p^F \vee q^T) \wedge p^T \wedge r^F} \Rightarrow^T \end{aligned}$$

The final clause set is $\Phi := \{p^F \vee q^F \vee r^T, p^F \vee q^T, p^T, r^F\}$

Resolution Proof:

1	$p^F \vee q^F \vee r^T$	initial
2	$p^F \vee q^T$	initial
3	p^T	initial
4	r^F	initial
5	$p^F \vee q^F$	resolve 1.3 with 4.1
6	q^F	resolve 3.1 with 5.1
7	p^F	resolve 2.2 with 6.1
7	\square	resolve 3.1 with 7.1

A resolution proof can be represented in a proof tree as shown in [figure 10](#) or in a graph as shown in [figure 11](#)

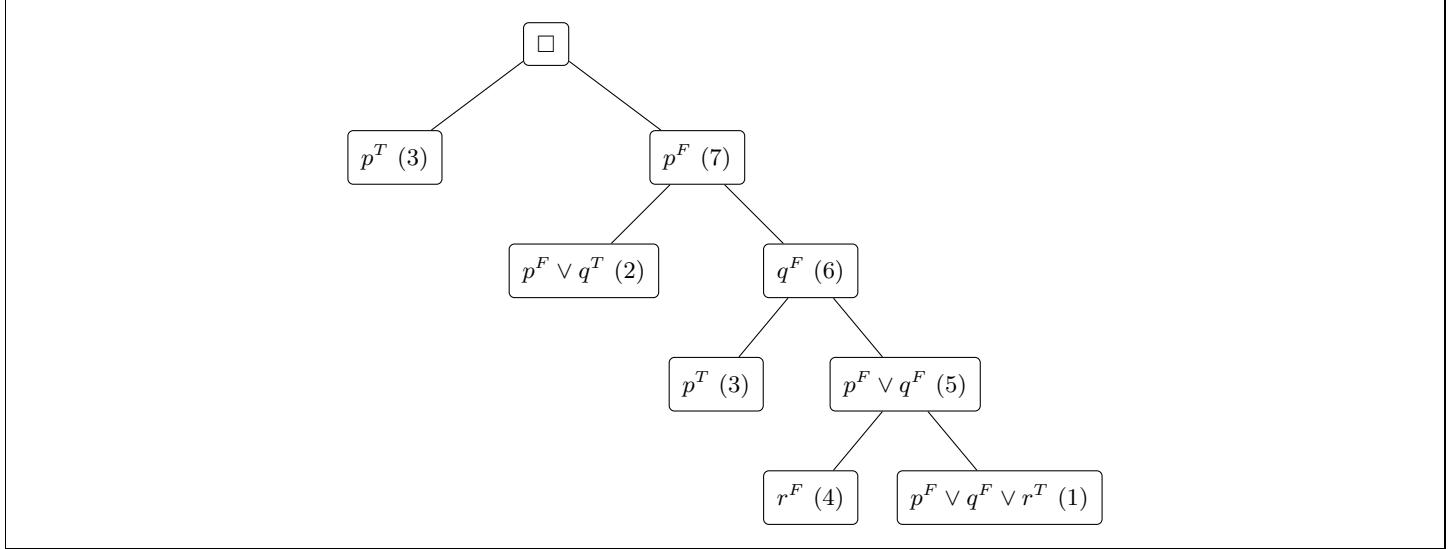


Figure 10: Resolution Proof Tree

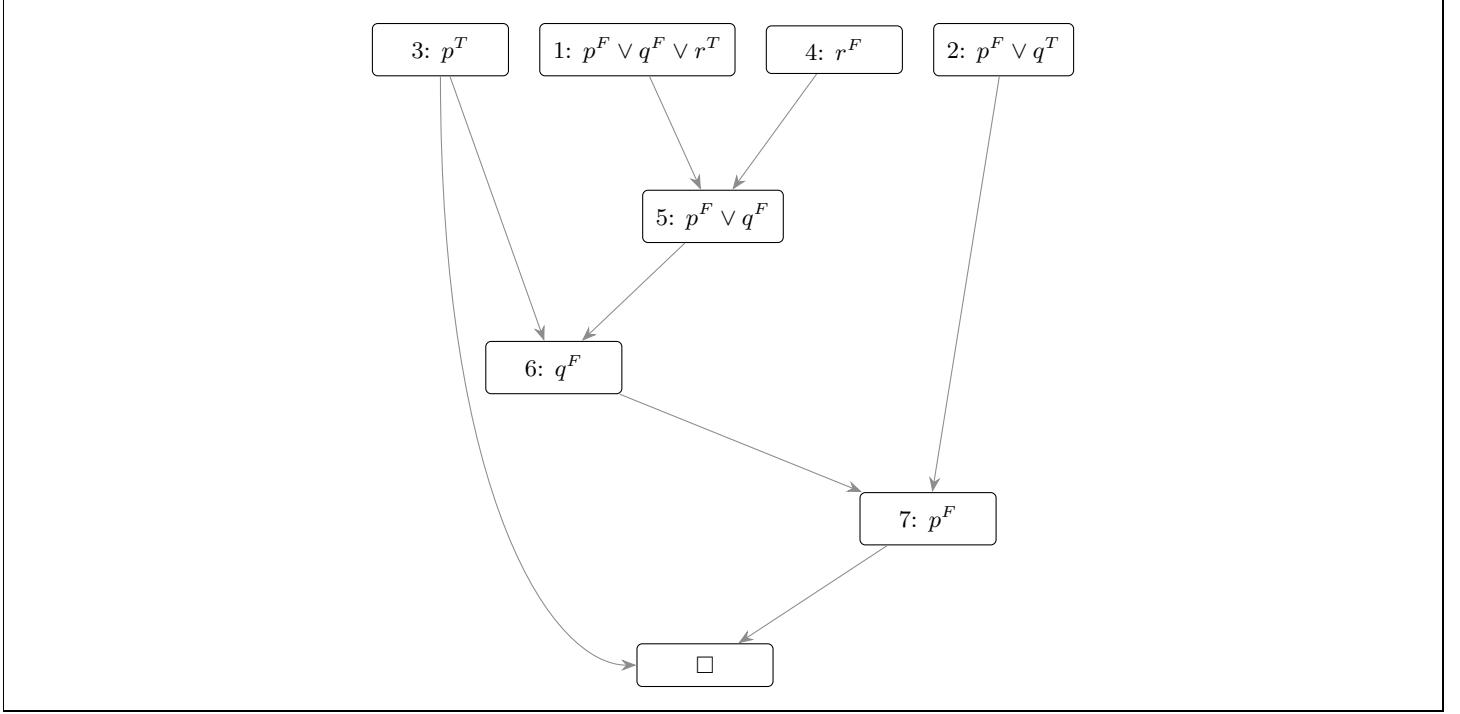


Figure 11: Resolution Proof Graph

Def 7.23. Clause Set Simplification: Let Δ be a clause set, $l \in \Delta$ is a unit clause, and Δ' be Δ where

- all clauses $l \vee C$ have been removed, and
- all clauses $\bar{l} \vee C$ have been shortened to C .

Then Δ is satisfiable iff Δ' is.

We call Δ' the clause set simplification of Δ w.r.t. l .

Note: as long as we have unit clauses, we can apply clause set simplification recursively, if we can derive the empty clause, we have a proof!

Example: Let $\Delta := \{p^F \vee q^F \vee r^T, p^F \vee q^T, p^T, r^F\}$

- Choose a unit clause, say p^T
- Remove any clause with p^T and shorten any clause with $p^F \vee C$ to just C
- $\Delta' := \{q^F \vee r^T, q^T, r^F\}$
- Choose a unit clause, say q^T
- Remove any clause with q^T and shorten any clause $q^F \vee C$ to just C
- $\Delta'' := \{r^T, r^F\}$
- Choose any unit clause, say r^T
- Remove any clause with r^T and shorten any clause $r^F \vee C$ to just C
- $\Delta''' := \{\square\}$

Using clause set simplification, we derived the empty clause without even resolving!

Note

If we apply clause set simplification to a satisfiable clause set, we can read off the model that satisfies the clause set (and we will end up with an empty set of clauses, not the the set containing the empty clause). For example, consider $\Delta := \{p^T, q^T \vee r^T, r^F\}$

- Choose a unit clause, say p^T
- $\Delta' := \{q^T \vee r^T, r^F\}$
- Choose a unit clause, say r^F
- $\Delta'' := \{q^T\}$
- Choose a unit clause, say q^T
- $\Delta''' := \emptyset$

The unit clauses we chose on the way correspond to the model φ that satisfies the clause set, namely $\varphi := \{p \mapsto T, r \mapsto F, q \mapsto T\}$. Which makes sense since $p \wedge (q \vee r) \wedge \neg r$ is indeed satisfiable under φ .

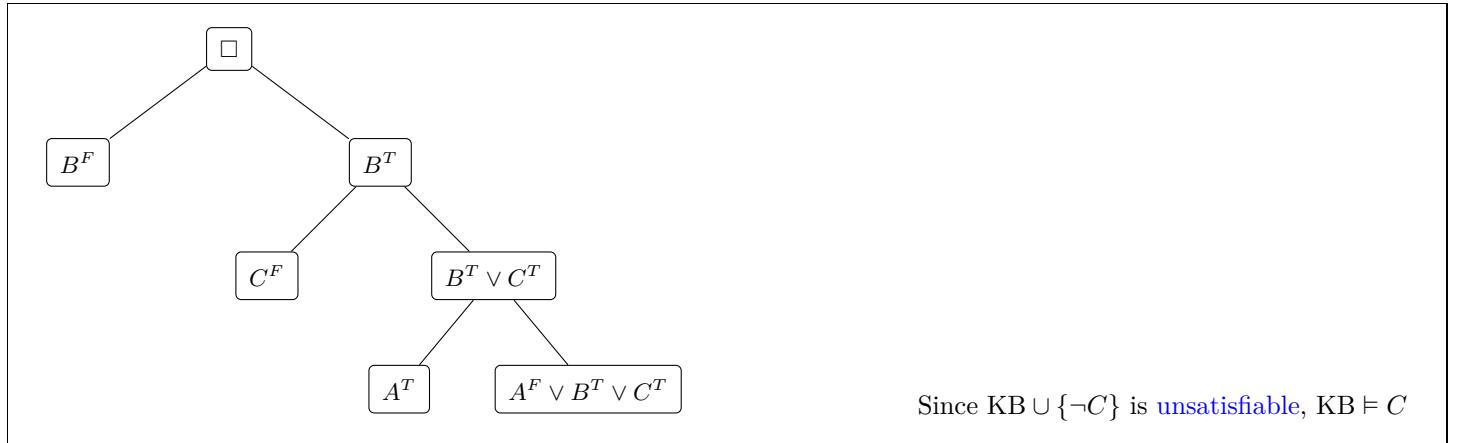
Example: Resolution in the real world

Consider we have a knowledge base $\text{KB} := \{A \Rightarrow B \vee C, A, \neg B\}$, we want to check if $\text{KB} \models C$. $\text{KB} \models C$ iff $\text{KB} \cup \{\neg C\}$ is unsatisfiable.

First we need to compute $\text{CNF}_0(A \Rightarrow B \vee C)$

- $\text{CNF}_0(A \Rightarrow B \vee C) = \neg A \vee B \vee C$

$$\text{KB} \cup \{\neg C\} := \{\neg A \vee B \vee C, A, \neg B, \neg C\} := \{A^F \vee B^T \vee C^T, A^T, B^F, C^F\}$$



Def 7.24. SAT: Given a propositional formula A , the Boolean Satisfiability Problem $\langle A, V \subset \mathcal{V}_{\text{PL}^0} \rangle$ is to decide whether or not A is satisfiable. We denote the class of all these problems with **SAT**. **SAT** problems are NP-Complete.

Def 7.25. : The tools that address **SAT** are commonly referred to as **SAT Solvers**.

Theorem 7.5. Given any constraint network $\gamma := \langle V, D, C \rangle$, we can in low-order polynomial time construct a CNF formula $A(\gamma)$ that is satisfiable iff γ is solvable.

SAT → CSP:

Given a **SAT** instance $S = \langle A, V \rangle$, we define a **CSP** instance $\gamma := \langle V', D, C \rangle$ and bijections f, f^{-1} mapping satisfying assignments of S to solutions of γ and vice versa:

- we define $V' := V$.
- we define $D := \bigcup_v D_v$ where $D_v := \{T, F\} \quad \forall v \in V'$
- the constraints C consist of a single higher-order constraint which is simply the formula $\rightsquigarrow C := \{A\}$
- The bijections f, f^{-1} are identity mappings because solutions are identical

CSP → SAT:

Given a **CSP** instance $\gamma := \langle V, D, C \rangle$, we define a **SAT** instance $S := \langle V', A \rangle$ and bijections f, f^{-1} :

Variables: For each $v \in V$ and each value $a \in D_v$, we introduce a new propositional variable $P_{v,a}$, V' contains all those variables:

$$V' := \{P_{v,a} \mid v \in V \wedge a \in D_v\}$$

Formula: The formula A is defined as the conjunction of three sets of constraints:

$$A := \Phi_{\text{at-least-one}} \wedge \Phi_{\text{at-most-one}} \wedge \Phi_{\text{consistent}}$$

- **At-least-one assignment:** Ensures that each variable v is assigned at least one value from its domain D_v :

$$\Phi_{\text{at-least-one}} = \bigwedge_{v \in V} \left(\bigvee_{a \in D_v} P_{v,a} \right)$$

- **At-most-one assignment:** Ensures that a variable v cannot be assigned more than one value by forbidding all pairs of distinct values:

$$\Phi_{\text{at-most-one}} = \bigwedge_{v \in V} \bigwedge_{\substack{a,b \in D_v \\ a \neq b}} (\neg P_{v,a} \vee \neg P_{v,b})$$

- **Consistency:** Ensures only assignments that satisfy the CSP constraints C_{vw} are allowed by forbidding inconsistent pairs (a,b) :

$$\Phi_{\text{consistent}} = \bigwedge_{\{v,w\} \subseteq V} \bigwedge_{(a,b) \notin C_{vw}} (\neg P_{v,a} \vee \neg P_{w,b})$$

Bijections:

- f maps a solution α of the **CSP** to a satisfying assignment φ for the **SAT** instance.

$$f(\alpha) = \varphi, \text{ such that } \forall v \in V, \forall a \in D_v : \varphi(P_{v,a}) = \begin{cases} T & \text{if } \alpha(v) = a \\ F & \text{otherwise} \end{cases}$$

- f^{-1} maps a satisfying assignment φ back to a **solution** α

$$f^{-1}(\varphi) = \alpha \text{ such that } \forall v \in V : \alpha(v) = a \Leftrightarrow \varphi(P_{v,a}) = T$$

Def 7.26. UR: Unit Resolution (UR) is a **test calculus** consisting of the following **inference rule**:

$$\frac{C \vee P^\alpha \quad P^\beta \quad \alpha \neq \beta}{C} \text{ UR}$$

It is a restricted form of \mathcal{R}_0 where at least one of the two **clauses** is a **unit clause**.

Def 7.27. UP: Unit Propagation (UP) is an iterative **clause set simplification** technique triggering a chain reaction of **simplifications** using only **UR**.

Def 7.28. Splitting: The process of picking a variable p and branching the search into two cases: one where p is assumed to be T , and one where p is assumed to be F , resulting in a **search tree**.

Def 7.29. DPLL: The **Davis Putnam (Logemann-Loverland) Procedure (DPLL)** is a **SAT solver** called on a **clause set** Δ and the empty assignments ϵ . It is the standard algorithm for deciding the **satisfiability** of a **clause set**:

1. Perform **Unit Propagation** until no more **unit clauses** exists.
2. Check if the **clause set** is empty (**satisfiable**) or contains an **empty clause** (**unsatisfiable**)
3. If neither, perform **splitting** on a variable and repeat.

The pseudocode for DPLL algorithm is shown in **Algorithm 3** and **Algorithm 4**.

Algorithm 3 DPLL

```

1: function DPLL( $\Delta, \varphi$ ) ▷ Returns assignment  $\varphi$  or unsatisfiable
2:    $\Delta' \leftarrow$  copy of  $\Delta$ 
3:    $\varphi' \leftarrow \varphi$ 
4:   while  $\Delta'$  contains a unit clause  $C = P^\alpha$  do ▷ Unit Propagation
5:      $\varphi' \leftarrow \varphi' \cup \{P \mapsto \alpha\}$ 
6:      $\Delta' \leftarrow \text{SIMPLIFY}(\Delta', P^\alpha)$ 
7:   end while
8:   if  $\square \in \Delta'$  then ▷ Termination Test: Contradiction
9:     return unsatisfiable
10:  end if
11:  if  $\Delta' = \emptyset$  then ▷ Termination Test: Success
12:    return  $\varphi'$ 
13:  end if
14:   $P \leftarrow \text{SELECT-UNASSIGNED-VARIABLE}(\Delta', \varphi')$  ▷ Splitting Rule
15:   $\varphi'' \leftarrow \varphi' \cup \{P \mapsto T\}$ 
16:   $\Delta'' \leftarrow \text{SIMPLIFY}(\Delta', P^T)$ 
17:   $res \leftarrow \text{DPLL}(\Delta'', \varphi'')$ 
18:  if  $res \neq$  unsatisfiable then
19:    return  $res$ 
20:  end if
21:   $\varphi'' \leftarrow \varphi' \cup \{P \mapsto F\}$ 
22:   $\Delta'' \leftarrow \text{SIMPLIFY}(\Delta', P^F)$ 
23:  return DPLL( $\Delta'', \varphi''$ )
24: end function

```

Algorithm 4 Simplify

```

1: function SIMPLIFY( $\Delta, P^\alpha$ )
2:    $\Delta' \leftarrow \emptyset$ 
3:   for each clause  $C \in \Delta$  do
4:     if  $P^\alpha \in C$  then
5:       continue ▷ Remove any clause that has  $P^\alpha$ 
6:     else if  $P^\beta \in C$  then
7:        $C' \leftarrow C \setminus \{P^\beta\}$  ▷ Remove  $P^\beta$  from the clause and keep the rest
8:        $\Delta' \leftarrow \Delta' \cup \{C'\}$ 
9:     else
10:       $\Delta' \leftarrow \Delta' \cup \{C\}$  ▷ Clause does not contain the variable  $P$  at all
11:    end if
12:   end for
13:   return  $\Delta'$ 
14: end function

```

DPLL Example: Let $\Delta := \{p^T \vee q^T \vee r^F, p^F \vee q^F, p^T \vee q^F, r^T\}$

- We start with the empty assignments $\varphi := \emptyset$
- We see a **unit clause** r^T , we assign r to T , hence $\varphi := \{r \mapsto T\}$
- We apply **UP** $\rightsquigarrow \Delta' := \{p^T \vee q^T, p^F \vee q^F, p^T \vee q^F\}$
- No **unit clauses** \rightsquigarrow apply **splitting**:
- Choose any variable and branch, say we choose p

Branch 1: Assume p^T

We copy the assignment $\varphi_1 := \{r \mapsto T\}$ and we copy the clause set Δ'_1

- we treat p^T as a **unit clause**, hence $\varphi_1 := \{r \mapsto T, p \mapsto T\}$
- we apply **UP** on Δ'_1
- $\Delta''_1 := \{q^F\}$
- we see a **unit clause** q^F , we assign, $\varphi_1 := \{r \mapsto T, p \mapsto T, q \mapsto F\}$
- we apply **UP** on Δ''
- $\Delta'''_1 := \emptyset$
- we return **satisfiable** with φ_1

Branch 2: Assume p^F

We copy the assignment $\varphi_2 := \{r \mapsto T\}$ and we copy the clause set Δ'_2

- we treat p^F as a **unit clause**, hence $\varphi_2 := \{r \mapsto T, p \mapsto F\}$
- we apply **UP** on Δ'_2
- $\Delta''_2 := \{q^T, q^F\}$
- we choose a **unit clause**, say q^T , we assign, $\varphi_2 := \{r \mapsto T, p \mapsto F, q \mapsto T\}$
- we apply **UP** on Δ''_2
- $\Delta'''_2 := \{\square\}$
- we return **unsatisfiable** for this branch.

The **DPLL** procedure can be visualized as a **search tree** as shown in figure 12

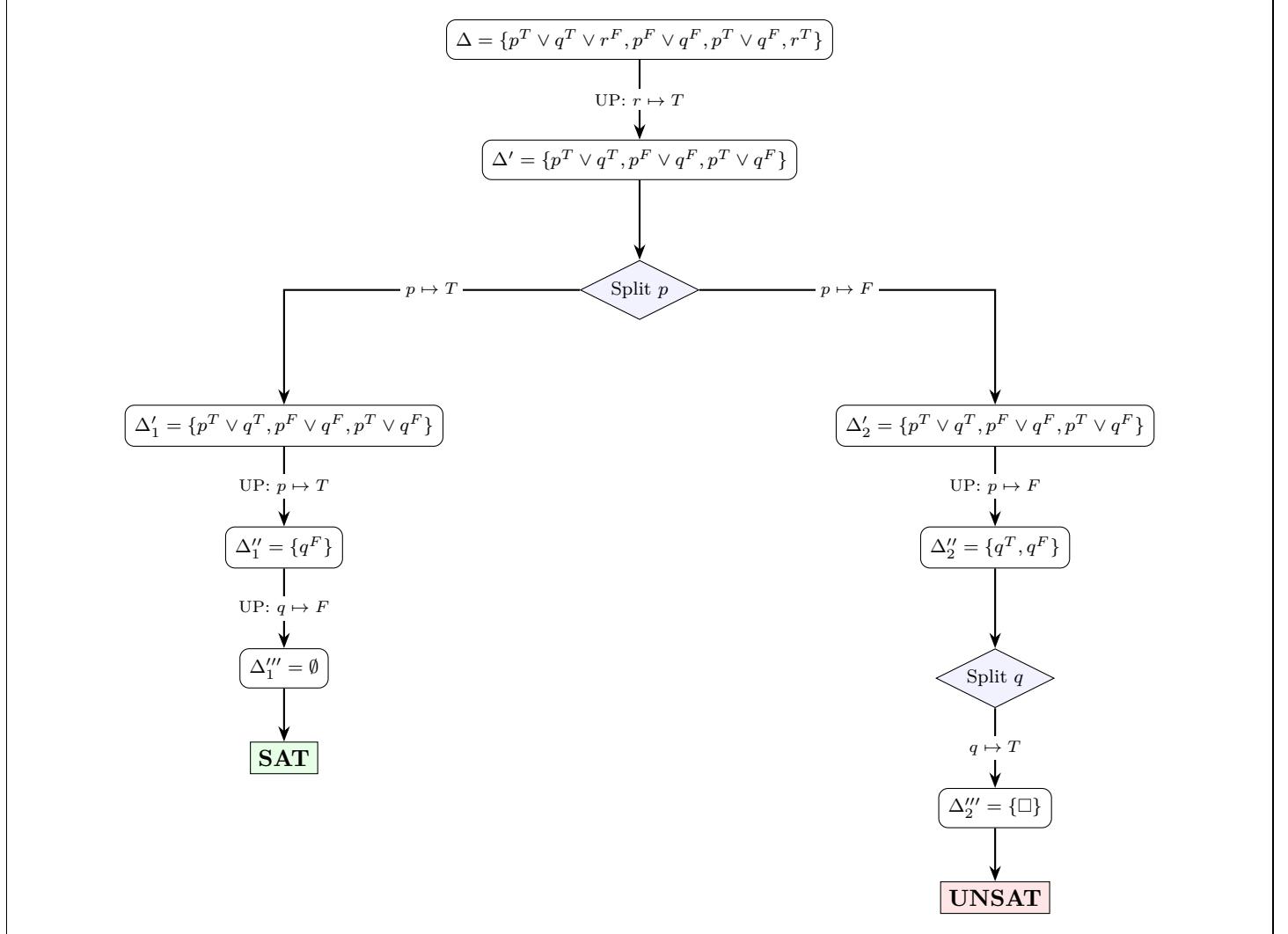


Figure 12: DPLL Search Tree

Theorem 7.6. **UP** is **sound**

Theorem 7.7. **UR** is **refutation-sound** (since \mathcal{R}_0 is)

Theorem 7.8. **UR** is not **refutation-complete**

Proof Sketch: **UR** makes only limited inference, as long as there are **unit clauses**. It does not guarantee to infer everything that can be inferred

Theorem 7.9. If **DPLL** returns **unsatisfiable** on Δ , then $\Delta \vdash_{\mathcal{R}_0} \square$ with a \mathcal{R}_0 -refutation

Observation: we can read off a [resolution proof](#) from a [DPLL](#) trace. From a (top-down) [DPLL tree](#), we generate a (bottom-up) [resolution proof](#) as shown in [figure 13](#).

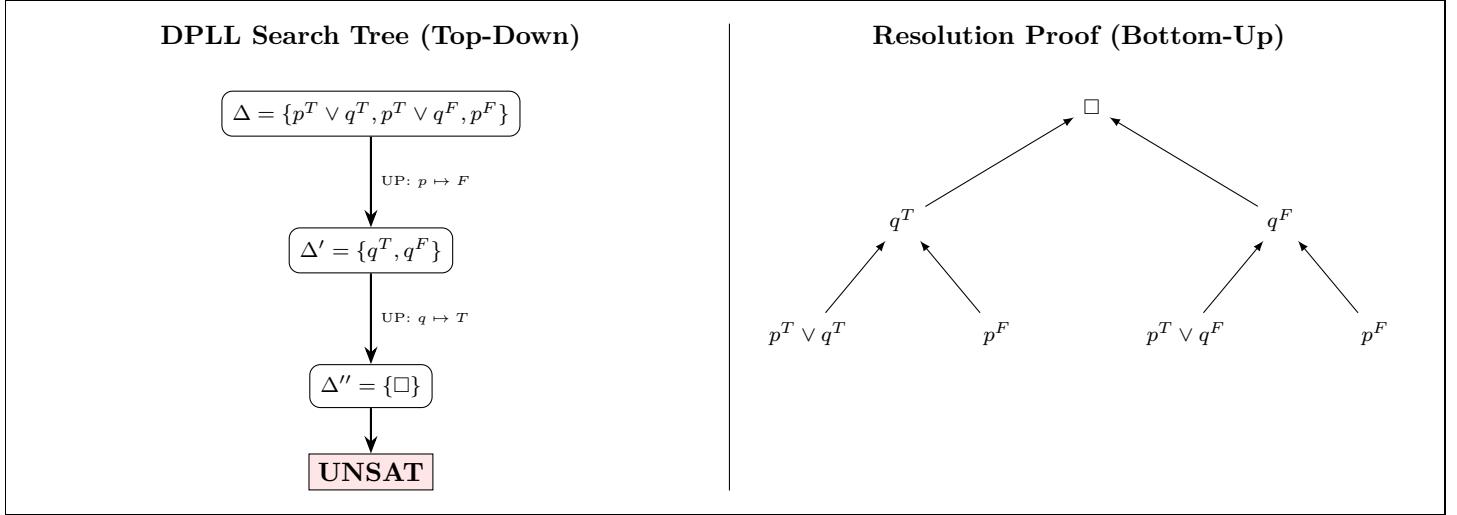


Figure 13: DPLL vs Resolution

8 First-Order Predicate Logic

Def 8.1. PL¹: First-Order (Predicate) Logic PL¹ is a **formal system** extensively used in mathematics, philosophy, linguistics, and computer science. It combines PL⁰ with the ability to quantify over **individuals**

Def 8.2. First-Order Signature: A First-Order Signature is a tuple $\Sigma := \langle \Sigma_1, \Sigma_0 \rangle$ where $\Sigma_1 := \Sigma^f \cup \Sigma^p \cup \Sigma^{sk}$:

- $\Sigma^f := \bigcup_{k \in \mathbb{N}} \Sigma_k^f$ of **function constants** (or **terms**), where members of Σ_k^f denote the k -ary **functions** on **individuals**
- $\Sigma^p := \bigcup_{k \in \mathbb{N}} \Sigma_k^p$ of **predicate constants**, where member of Σ_k^p denote k -ary **relations** among individuals
- $\Sigma^{sk} := \bigcup_{k \in \mathbb{N}} \Sigma_k^{sk}$ of **Skolem constants** that act as witness constructors
- All are **pairwise disjoint**, **countable sets** of symbols for each $k \in \mathbb{N}$.

We also assume a **set** of **individual variables** $V_i := \{X, Y, Z, \dots\}$ which we can quantify over them.

Note

Def 8.2 is the full FOL Signature. In PL^{nq}, we did not explicitly define Σ_0 (assumed to be there) and we did not need Σ^{sk} since no quantification over **individuals** was allowed. That is why in Def 6.20 we only mentioned what PL^{nq} actually uses of the **full FOL Signature**

Note

In PL^{nq}, we defined terms and formulae in Def 6.22 and Def 6.23 as follows:

- We denote the **set** of all well-formed **terms** over a **FOL Signature** Σ with $wff_t(\Sigma)$, and the **closed** ones with $cwff_t(\Sigma)$
- We denote the **set** of all well-formed **formulae** over a **FOL Signature** Σ with $wff_o(\Sigma)$, and the **closed** ones with $cwff_o(\Sigma)$

Def 8.3. PL¹ Terms: The **set** $wff_t(\Sigma_1, V_i)$ of **well-formed terms** over the signature Σ_1 and variables V_i is defined by the following **grammar**:

$$\begin{aligned} f^k &\in \Sigma_k^f \cup \Sigma_k^{sk} \\ X &\in V_i \\ t &::= X \mid f^k(t_1, \dots, t_k) \end{aligned}$$

Def 8.4. PL¹ Propositions: The **set** $wff_o(\Sigma_1, V_i)$ of **well-formed formulae** over the signature Σ_1 and variables V_i is defined by the following **grammar**:

$$\begin{aligned} p^k &\in \Sigma_k^p \\ t_i &\in wff_t(\Sigma_1, V_i) \\ X &\in V_i \\ A &::= p^k(t_1, \dots, t_k) \mid \top \mid \neg A \mid A \wedge A \mid \forall X. A \end{aligned}$$

Def 8.5. Universal Quantifier: The **universal quantifier** \forall is a binding operator used to express $\forall X. A$, i.e. a **formula** A holds for all possible values of an **individual variable** $X \in V_i$

Note

Notice that we only need \top, \wedge, \neg as connectives because the others ($\perp, \vee, \Rightarrow, \Leftrightarrow$) are defined via **abbreviations**:

- $\perp := \neg \top$
- $A \vee B := \neg(\neg A \wedge \neg B)$
- $A \Rightarrow B := \neg A \vee B$
- $A \Leftrightarrow B := (A \Rightarrow B) \wedge (B \Rightarrow A)$

Def 8.6. Existential Quantifier: The **existential quantifier** \exists is a binding operator defined as an **abbreviation** for a negated universal statement: $\exists X. A := \neg(\forall X. \neg A)$. It allows us to express that at least one **individual** satisfies the **formula** A .

Note

Remember: Def 6.8 , Def 6.9 for PL^0 . We have a similar notion of free variables in PL^1 that help us define closed/ground PL^1 formulae.

Def 8.7. Free Variables: An occurrence of a variable X is **free** in a **formula** A if it is not within the scope of a binder. We define the **set** of free variables in A ($\text{free}(A)$) recursively as follows:

- **For Terms** ($t \in \text{wff}_t(\Sigma_1, V_t)$)
 - $\text{free}(X) = \{X\}$
 - $\text{free}(f^k(t_1, \dots, t_k)) := \bigcup_{i=1}^k \text{free}(t_i)$
- **For Formulae** ($A \in \text{wff}_o(\Sigma_1, V_t)$)
 - $\text{free}(p^k(t_1, \dots, t_k)) := \bigcup_{i=1}^k \text{free}(t_i)$
 - $\text{free}(\top) := \emptyset$
 - $\text{free}(\neg A) := \text{free}(A)$
 - $\text{free}(A \wedge B) := \text{free}(A) \cup \text{free}(B)$
 - $\text{free}(\forall X.A) := \text{free}(A) \setminus \{X\}$

Def 8.8. Bound Variables: An occurrence of a variable X is **bound** if it occurs within the scope of a quantifier. We define the **set** of bound variables $\text{BVar}(A)$ as the **set** of all variables that are *captured* by a binder:

- **For Terms** ($t \in \text{wff}_t(\Sigma_1, V_t)$)
 - $\text{BVar}(t) := \emptyset$ (*variables in terms are always free until a formula provides a binder*)
- **For Formulae** ($A \in \text{wff}_o(\Sigma_1, V_t)$)
 - $\text{BVar}(p^k(t_1, \dots, t_k)) := \emptyset$
 - $\text{BVar}(\neg A) := \text{BVar}(A)$
 - $\text{BVar}(A \wedge B) := \text{BVar}(A) \cup \text{BVar}(B)$
 - $\text{BVar}(\forall X.A) := \text{BVar}(A) \cup \{X\}$

Def 8.9. Ground Formulae: A PL^1 formula A is called **ground/closed** iff $\text{free}(A) := \emptyset$. A closed **formula** is called a sentence. We denote the **set** of all **ground terms** with $\text{cwff}_t(\Sigma_1, V_t)$ and the **set** of all sentences with $\text{cwff}_o(\Sigma_1, V_t)$

Def 8.10. Alphabetical Variants: **Bound variables** can be **renamed**; specifically, if $\forall X.B$ is a sub-formula of A , let A' be the result of replacing $\forall X.B$ in A with $\forall Y.B'$, where B' is obtained from B by replacing all occurrences of $X \in \text{free}(B)$ with a new variable Y that does not occur in A . We call A' an **alphabetical variant** of A (and vice versa).

Def 8.11. PL¹ Universe: PL^1 uses the universe $\mathcal{D}_{\text{PL}^1} := \mathcal{D}_0 \cup \mathcal{D}_t$ where $\mathcal{D}_0 = \{T, F\}$ is the **set** of truth values and $\mathcal{D}_t \neq \emptyset$ is a non-empty **set** of **individuals**

Def 8.12. Interpretation in PL¹: The interpretation function in PL^1 **assigns** values to **constants**:

1. We use the **interpretation** from PL^0
 - $\mathcal{I}(\neg) : \mathcal{D}_0 \rightarrow \mathcal{D}_0; T \mapsto F, F \mapsto T$
 - $\mathcal{I}(\wedge) : \mathcal{D}_0 \times \mathcal{D}_0 \rightarrow \mathcal{D}_0; \langle \alpha, \beta \rangle \mapsto T, \text{ iff } \alpha = \beta = T$
 - $\mathcal{I}(\top) = T$
 - $\mathcal{I}(\perp) = F$
2. We interpret **individual constants** as **individuals**: $\mathcal{I} : \Sigma_0^f \rightarrow \mathcal{D}_t$
3. We interpret **function constants** as **functions**: $\mathcal{I} : \Sigma_{k \neq 0}^f \rightarrow \mathcal{D}_t^{k \neq 0} \rightarrow \mathcal{D}_t$
4. We interpret **predicate constants** as **relations**: $\mathcal{I} : \Sigma_k^p \rightarrow \mathcal{P}(\mathcal{D}_t^k)$

Def 8.13. PL¹ Value Function: Given a model $\langle \mathcal{D}, \mathcal{I} \rangle$, the value function \mathcal{I}_φ is recursively defined:

1. $\mathcal{I}_\varphi : \text{wff}_t(\Sigma_1, V_t) \rightarrow \mathcal{D}_t$ assigns values to **terms**

- $\mathcal{I}_\varphi(X) := \varphi(X)$, and
- $\mathcal{I}_\varphi(f(A_1, \dots, A_k)) := \mathcal{I}(f)(\mathcal{I}_\varphi(A_1), \dots, \mathcal{I}_\varphi(A_k))$

2. $\mathcal{I}_\varphi : \text{wff}_o(\Sigma_1, V_\iota) \rightarrow \mathcal{D}_o$ assigns values to **formulae**

- $\mathcal{I}_\varphi(\top) = \mathcal{I}(\top) = T$
- $\mathcal{I}_\varphi(\neg A) := \mathcal{I}(\neg)(\mathcal{I}_\varphi(A))$
- $\mathcal{I}_\varphi(A \wedge B) := \mathcal{I}(\wedge)(\mathcal{I}_\varphi(A), \mathcal{I}_\varphi(B))$
- $\mathcal{I}_\varphi(p(A_1, \dots, A_k)) := T$, iff $\langle \mathcal{I}_\varphi(A_1), \dots, \mathcal{I}_\varphi(A_k) \rangle \in \mathcal{I}(p)$
- $\mathcal{I}_\varphi(\forall X.A) := T$, iff $\mathcal{I}_{\varphi,[a/X]}(A) = T$ for all $a \in \mathcal{D}_\iota$

Def 8.14. Assignment Extension: Let $\varphi : V_\iota \rightarrow \mathcal{D}_\iota$ be a **variable assignment** and $a \in \mathcal{D}_\iota$. The **extension** of φ by a for X , denoted by $\varphi, [a/X]$ is a variable assignment defined as:

$$\varphi, [a/X](Y) := \begin{cases} a & \text{if } Y = X \\ \varphi(Y) & \text{if } Y \neq X \end{cases}$$

Equivalently, viewing the assignment as a set of ordered pairs:

$$\varphi, [a/X] = \{(Y, \varphi(Y)) \mid Y \in V_\iota \setminus \{X\}\} \cup \{(X, a)\}$$

This assignment coincides with φ for all variables except X , where it maps to the individual a .

Def 8.15. Expression Language: Let signature Σ and variables \mathcal{V} be **disjoint sets** and G a **grammar** whose vocabulary is $\Sigma \cup \mathcal{V}$, then we call $\langle \Sigma, \mathcal{V}, G \rangle$ an **expression language**, and denote the **language** of G with $\text{wfe}(\Sigma, \mathcal{V})$: the **set of well-formed expressions**.

Note

For **PL**¹, we have:

$$\text{wfe}(\Sigma_1, \mathcal{V}_\iota) := \text{wff}_o(\Sigma_1, V_\iota) \cup \text{wff}_t(\Sigma_1, V_\iota)$$

Def 8.16. Support: Let $f : A \rightarrow B$ be a **function**. The **support** of f , denoted by $\text{supp}(f)$, is the **set** of all elements in the **domain** A for which the **function** does not return a "default" or "identity" value.

Def 8.17. Substitution: Let $\text{wfe}(\Sigma, \mathcal{V})$ be an **expression language**, then we call $\sigma : \mathcal{V} \rightarrow \text{wfe}(\Sigma, \mathcal{V})$ a **substitution** iff the **support** $\text{supp}(\sigma) := \{X \mid (X, A) \in \sigma \wedge X \neq A\}$ of σ is **finite**. We denote the **empty substitution** with ϵ .

Def 8.18. : We can **discharge** a variable X from a **substitution** σ by setting $\sigma_{-X} := \sigma, [X/X]$

Def 8.19. : Let σ be a **substitution**, then we call $\text{intro}(\sigma) := \bigcup_{X \in \text{supp}(\sigma)} \text{free}(\sigma(X))$ the **set** of variables **introduced** by σ .

Example: consider the **formula** $A := \forall X.p(X, Y)$ and the **substitution** $\sigma := \{[Z/Y]\}$:

- $\text{supp}(\sigma) = \{Y\}$
- $\text{free}(\sigma(Y)) = \text{free}(Z) = \{Z\}$
- $\text{intro}(\sigma) = \text{free}(\sigma(Y)) = \{Z\}$

Def 8.20. Substitution Application: We define substitution application by:

- $\sigma(c) = c$ for $c \in \Sigma$
- $\sigma(X) = A$ iff $X \in \mathcal{V}$ and $(X, A) \in \sigma$
- $\sigma(f(A_1, \dots, A_n)) = f(\sigma(A_1), \dots, \sigma(A_n))$
- $\sigma(\forall X.A) = \forall X.\sigma_{-X}(A)$

Note

The concept of **support** is useful to handle **finiteness** in systems that are **infinite**. For example, in **PL**¹, the **set** of variables \mathcal{V}_ι is **infinite**. However, when we **apply a substitution**, we don't want to deal with an **infinite** number of changes. By requiring the **support** of a **substitution** to be **finite**, we ensure that only a manageable, **countable** number of variables are being modified, while the **infinite** rest of them simply stay the same (mapping to their "identity" value).

Substitution Example: consider the formula $g(x, y, h(z))$, and we want to apply the substitution $\sigma := \{x \mapsto a, y \mapsto f(b), z \mapsto a\}$ we get the formula $g(a, f(b), h(a))$

Note

Usually we use another notation for writing the substitution $\sigma := \{x \mapsto a, y \mapsto f(b), z \mapsto a\}$ which is $[a/x], [f(b)/y], [a/z]$ where $[A/X]$ (read as A for X i.e. substitute X with A) $\equiv X \mapsto A \equiv (X, A) \in \sigma$

Def 8.21. Substitution Extension: Let σ be a substitution, then we denote the extension of σ with $[A/X]$ by $\sigma, [A/X]$ and define it as $\{(Y, B) \in \sigma \mid Y \neq X\} \cup \{(X, A)\}$.

Def 8.22. Capture-Avoiding Substitution Application: Let σ be a substitution, A a formula, and A' an alphabetical variant of A , such that $\text{intro}(\sigma) \cap \text{BVar}(A') = \emptyset$. Then we define capture-avoiding substitution application via $\sigma(A) := \sigma(A')$

Note

We said $\sigma(\forall X.A) = \forall X.\sigma_{-X}(A)$ but this can lead to variable capture, i.e. $[f(X)/Y](\forall X.p(X, Y))$ would evaluate to $\forall X.p(X, f(X))$ where the second occurrence of X is now bound whereas it was free before.

The solution for this is to rename the bound variable X in $\forall X.p(X, Y)$ before applying the substitution and there where we need capture-avoiding substitution application

Example: we want to apply $\sigma := \{[f(X)/Y]\}$ to the formula $A = \forall X.p(X, Y)$

- $\text{intro}(\sigma) \cap \text{BVar}(A) = \{X\} \cap \{X\} = \{X\}$
- Hence, we need to find an alphabetical variant A' for A , say $A' = \forall Z.p(Z, Y)$
- Now $\text{intro}(\sigma) \cap \text{BVar}(A') = \{X\} \cap \{Z\} = \emptyset$
- Hence, we define $\sigma(A) = \sigma(A')$
- $\sigma(A') = \sigma(\forall Z.p(Z, Y)) = \forall Z.\sigma_{-Z}(p(Z, Y))$
- $[f(X)/Y](p(Z, Y)) = p(Z, f(X))$
- $\sigma(A) = \sigma(A') = \forall Z.p(Z, f(X))$

Lemma 8.1. Let A and B be terms, then $\mathcal{I}_\varphi([B/X](A)) = \mathcal{I}_\psi(A)$, where $\psi = \varphi, [\mathcal{I}_\varphi(B)/X]$.

Proof. By induction on the depth of A :

1. depth = 0

Then A is either a variable or a constant. If A is variable, say Y , we have two cases $Y = X$ and $Y \neq X$:

(a) $A = Y = X$:

then $\mathcal{I}_\varphi([B/X](A)) = \mathcal{I}_\varphi([B/X](X)) = \mathcal{I}_\varphi(B) = \psi(X) = \mathcal{I}_\psi(X) = \mathcal{I}_\psi(A)$

(b) $A = Y \neq X$:

then $\mathcal{I}_\varphi([B/X](A)) = \mathcal{I}_\varphi([B/X](Y)) = \mathcal{I}_\varphi(Y) = \varphi(Y) = \psi(Y) = \mathcal{I}_\psi(Y) = \mathcal{I}_\psi(A)$

(c) A is a constant \rightsquigarrow analogous to 1.b

2. depth > 0

then $A = f(A_1, \dots, A_n)$ and we have

$$\begin{aligned} \mathcal{I}_\varphi([B/X](A)) &= \mathcal{I}(f)(\mathcal{I}_\varphi([B/X](A_1)), \dots, \mathcal{I}_\varphi([B/X](A_n))) \\ &= \mathcal{I}(f)(\mathcal{I}_\psi(A_1), \dots, \mathcal{I}_\psi(A_n)) \\ &= \mathcal{I}_\psi(A) \end{aligned}$$

by induction hypothesis

□

Lemma 8.2. Let A and B be propositions, then $\mathcal{I}_\varphi([B/X]A) = \mathcal{I}_\psi(A)$, where $\psi = \varphi, [\mathcal{I}_\varphi(B)/X]$.

Proof. By induction on the number of n connectives and quantifiers in A :

1. $n = 0$

then A is an **atomic formula**, and we can argue like in the induction step of the [Lemma 8.1](#)

2. $n > 0$ and $A = \neg B$ or $A = C \circ D$

Here we argue like in the induction step of [Lemma 8.1](#) as well

3. $n > 0$ and $A = \forall Y.C$ where ([WLOG](#)) $X \neq Y$ (otherwise, [rename](#))

(a) then $\mathcal{I}_\psi(A) = \mathcal{I}_\psi(\forall Y.C) = T$, iff $\mathcal{I}_{\psi,[a/Y]}(C) = T$ for all $a \in \mathcal{D}_\iota$

(b) But $\mathcal{I}_{\psi,[a/Y]}(C) = \mathcal{I}_{\varphi,[a/Y]}([B/X](C)) = T$, by induction hypothesis.

(c) So $\mathcal{I}_\psi(A) = \mathcal{I}_\varphi(\forall Y.[B/X](C)) = \mathcal{I}_\varphi([B/X](\forall Y.C)) = \mathcal{I}_\varphi([B/X](A))$

□

Def 8.23. \mathcal{ND}_1 : The First-Order Natural Deduction Calculus extends \mathcal{ND}_0 by the following four [inference rule](#):

$$\frac{A}{\forall X.A} \forall I^*$$

$$\frac{\forall X.A}{[B/X](A)} \forall E$$

* means that A does not depend on any hypothesis in which X is free

$$\frac{\frac{[B/X](A)}{\exists X.A} \exists I \quad \frac{\begin{array}{c} [[c/X](A)]^1 \\ \vdots \\ C \end{array}}{c \in \sum_0^{sk} \text{new}} \exists E^1}{C} \exists E^1$$

Def 8.24. \mathcal{ND}_\vdash^1 : The [inference rules](#) of the **First-Order Sequent Style Natural Deduction Calculus** consist of those from \mathcal{ND}_\vdash^0 plus the following quantifiers rules:

$$\frac{\Gamma \vdash A \quad X \notin \text{free}(\Gamma)}{\Gamma \vdash \forall X.A} \forall I$$

$$\frac{\Gamma \vdash \forall X.A}{\Gamma \vdash [B/X](A)} \forall E$$

$$\frac{\Gamma \vdash [B/X](A)}{\Gamma \vdash \exists X.A} \exists I$$

$$\frac{\Gamma \vdash \exists X.A \quad \Gamma, [c/X]A \vdash C \quad c \in \Sigma_0^{\text{sk new}}}{\Gamma \vdash C} \exists E^1$$

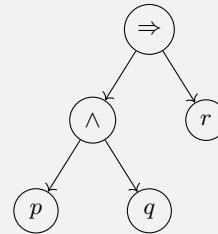
Def 8.25. PL_\equiv^1 : We extend PL^1 with a new logical constant for **equality** $\equiv \Sigma_2^p$ and fox its [interpretation](#) to $\mathcal{I}(=) := \{(x, x) \mid x \in \mathcal{D}_\iota\}$. We call the extended logic **First-Order Logic with Equality**.

Def 8.26. Position: A position is a finite sequence of natural numbers $p = \langle i_1, i_2, \dots, i_n \rangle$ that describes a path from the root of a [well-formed expression](#) to a specific sub-node. For an [expression](#) A , the subexpression at position p is denoted by $A|_p$. We write $C[A]_p$ to indicate that the expression C contains the subexpression A at position p . If A is an [atomic formula](#), we call p an **occurrence** of A in C .

Note

Example: consider $C := (p \wedge q) \Rightarrow r$

- Position $\langle 1 \rangle$ is the subexpression $(p \wedge q)$
- Position $\langle 1, 1 \rangle$ is the [occurrence](#) of the [atom](#) p
- Position $\langle 2 \rangle$ is the [occurrence](#) of the [atom](#) r



Def 8.27. Replacement: Let p be a [position](#), then $[A/p]C$ is the [expression](#) obtained from C by [replacing](#) the subexpression at p by A

Def 8.28. \mathcal{ND}_\equiv^1 : The **First-Order Logic with Equality Natural Deduction Calculus** extends \mathcal{ND}_1 by the following two [inference rule](#):

$$\overline{A = A} = I$$

$$\frac{A = B \quad C[A]_p}{[B/p]C} = E$$

Note

equivalence (\Leftrightarrow) behaves exactly as equality ($=$)

Def 8.29. : $\Leftrightarrow I$ is derivable and $\Leftrightarrow E$ is admissible in \mathcal{ND}_1 :

$$\overline{A \Leftrightarrow A} \Leftrightarrow I$$

$$\frac{A \Leftrightarrow B \quad C[A]_p}{[B/p]C} \Leftrightarrow E$$

Figure 14 shows all inference rules of the natural deduction calculus, i.e. the union of \mathcal{ND}_0 , \mathcal{ND}_1 , \mathcal{ND}_\equiv^1 , and equivalence rules

$$\begin{array}{c}
 \frac{A \quad B}{A \wedge B} \wedge I \qquad \frac{A \wedge B}{A} \wedge E_l \qquad \frac{A \wedge B}{B} \wedge E_r \\
 \begin{array}{c} [A]^1 \\ \vdots \\ \dot{B} \\ \hline A \Rightarrow B \end{array} \Rightarrow I^1 \qquad \qquad \qquad \frac{A \Rightarrow B \quad A}{B} \Rightarrow E \\
 \hline A \vee \neg A \quad \mathcal{TND} \\
 \frac{}{A \Leftrightarrow A} \Leftrightarrow I \qquad \qquad \qquad \frac{A \Leftrightarrow B \quad C[A]_p}{[B/p]C} \Leftrightarrow E \\
 \frac{A}{A \vee B} \vee I_l \qquad \qquad \qquad \frac{B}{A \vee B} \vee I_r \\
 \begin{array}{c} [A]^1 \quad [B]^1 \\ \vdots \quad \vdots \\ \dot{C} \quad \dot{C} \\ \hline C \end{array} \frac{}{\vee E^1} \\
 \frac{[A]^1 \quad [A]^1}{\begin{array}{c} \vdots \\ \vdots \\ \dot{C} \quad \neg C \\ \hline \neg A \end{array}} \neg I^1 \qquad \qquad \qquad \frac{\neg \neg A}{A} \neg E \\
 \frac{\neg A \quad A}{\perp} \perp I \qquad \qquad \qquad \frac{\perp}{A} \perp E \\
 \frac{A}{\forall X.A} \forall I^* \qquad \qquad \qquad \frac{\forall X.A}{[B/X](A)} \forall E
 \end{array}$$

* means that A does not depend on any hypothesis in which X is free

$$\begin{array}{c}
 \frac{[B/X](A)}{\exists X.A} \exists I \qquad \qquad \qquad \frac{\exists X.A \quad \begin{array}{c} [[c/X](A)]^1 \\ \vdots \\ C \\ c \in \sum_0^{sk} \text{new} \end{array}}{C} \exists E^1 \\
 \hline \overline{A = A} = I \qquad \qquad \qquad \frac{A = B \quad C[A]_p}{[B/p]C} = E
 \end{array}$$

Figure 14: All Natural Deduction Rules

9 Automated Theorem Proving in First-Order Logic

Def 9.1. \mathcal{T}_1 : The Standard First-Order Tableau Calculus extends \mathcal{T}_0 with the following inference rules

$$\frac{(\forall X.A)^T \quad C \in \text{cwf}_\ell(\Sigma)}{([C/X](A))^T} \mathcal{T}_1 \forall \quad \frac{(\forall X.A)^F \quad c \in \Sigma_0^{sk} \text{ new}}{([c/X]A)^F} \mathcal{T}_1 \exists$$

Note

Problem: The rule $\mathcal{T}_1 \forall$ displays a case of "*don't know indeterminism*": to find a [refutation](#) we have to guess a formula C from the [infinite set](#) $\text{cwf}_\ell(\Sigma)$.

For [proof search](#), this means $\mathcal{T}_1 \forall$ is [infinitely branching](#) in general

Def 9.2. \mathcal{T}_1^f : The Free Variable Tableau Calculus extends \mathcal{T}_0 with the following inference rules

$$\frac{(\forall X.A)^T \quad Y \text{ new}}{([Y/X](A))^T} \mathcal{T}_1^f \forall \quad \frac{(\forall X.A)^F \quad \text{free}(\forall X.A) = \{X^1, \dots, X^k\} \quad f \in \Sigma_k^{sk} \text{ new}}{([f(X^1, \dots, X^k)/X]A)^F} \mathcal{T}_1^f \exists$$

and generalizes its cut rule $\mathcal{T}_0 \perp$ to:

$$\frac{\begin{array}{c} A^\alpha \\ \vdots \\ B^\beta \quad (\alpha \neq \beta) \quad \sigma(A) = \sigma(B) \\ \perp : \sigma \end{array}}{\mathcal{T}_1^f \perp}$$

\mathcal{T}_1^f instantiates the whole tableau by σ

Def 9.3. : Derivable rules in \mathcal{T}_1^f :

$$\frac{(\exists X.A)^F \quad Y \text{ new}}{([Y/X](A))^F} \quad \frac{(\exists X.A)^T \quad \text{free}(\forall X.A) = \{X^1, \dots, X^k\} \quad f \in \Sigma_k^{sk} \text{ new}}{([f(X^1, \dots, X^k)/X](A))^T}$$

Combining \mathcal{T}_0 and \mathcal{T}_1^f we get the [inference rules](#) shown in [figure 15](#):

$\frac{(A \wedge B)^T}{\begin{matrix} A^T \\ B^T \end{matrix}} \mathcal{T}_0 \wedge$	$\frac{(A \wedge B)^F}{A^F \mid B^F} \mathcal{T}_0 \vee$
$\frac{(\neg A)^T}{A^F} \mathcal{T}_0 \neg^T$	$\frac{(\neg A)^F}{A^T} \mathcal{T}_0 \neg^F$
$\frac{\begin{matrix} A^\alpha \\ \vdots \\ A^\beta \quad (\alpha \neq \beta) \end{matrix}}{\perp} \mathcal{T}_0 \perp$	
$\frac{(\forall X.A)^T \quad Y \text{ new}}{([Y/X](A))^T} \mathcal{T}_1^f \forall$	$\frac{(\forall X.A)^F \quad \text{free}(\forall X.A) = \{X^1, \dots, X^k\} \quad f \in \Sigma_k^{sk} \text{ new}}{([f(X^1, \dots, X^k)/X]A)^F} \mathcal{T}_1^f \exists$
$\frac{\begin{matrix} A^\alpha \\ \vdots \\ B^\beta \quad (\alpha \neq \beta) \quad \sigma(A) = \sigma(B) \end{matrix}}{\perp : \sigma} \mathcal{T}_1^f \perp$	
$\frac{(A \Rightarrow B)^T}{A^F \mid B^T}$	
$\frac{(A \vee B)^T}{A^T \mid B^T}$	$\frac{(A \Rightarrow B)^F}{\begin{matrix} A^T \\ B^F \end{matrix}}$
$\frac{(A \iff B)^T}{\begin{matrix} A^T & & A^F \\ B^T & & B^F \end{matrix}}$	$\frac{(A \vee B)^F}{\begin{matrix} A^F \\ B^F \end{matrix}}$
$\frac{(\exists X.A)^F \quad Y \text{ new}}{([Y/X](A))^F}$	$\frac{(\exists X.A)^T \quad \text{free}(\forall X.A) = \{X^1, \dots, X^k\} \quad f \in \Sigma_k^{sk} \text{ new}}{([f(X^1, \dots, X^k)/X](A))^T} \mathcal{T}_1^f$

Figure 15: $\mathcal{T}_0 \cup \mathcal{T}_1^f$

Def 9.4. Unification: For given terms A_1, A_2 , unification is the problem of finding a substitution σ (called unifier), such that $\sigma(A_1) = \sigma(A_2)$

Def 9.5. Unification Problem: We call a formula $A^1 =? B^1 \wedge \dots \wedge A^n =? B^n$ a unification problem iff $A^i, B^i \in \text{wff}_t(\Sigma_1, V)$

Note

We consider unification problems as sets of equations. \wedge here is associative, commutative, and idempotent. We consider equations as two-element multisets, $=?$ here is commutative

Def 9.6. : A substitution is called a unifier for a unification problem \mathcal{E} (and thus \mathcal{E} is unifiable), iff it is a (simultaneous) unifier for all pairs in \mathcal{E}

Def 9.7. : The solution for a unification problem $U(A_1, A_2)$ is the set of unifiers $\{\sigma \mid \sigma(A_1) = \sigma(A_2)\}$. For example, let $\mathcal{E} := f(X) =? f(g(Y))$, solutions are, e.g.

- $[g(a)/X], [a/Y]$
- $[g(g(a))/X], [g(a)/Y]$

- $[g(Z)/X], [Z/Y]$
- $[g(Y)/X]$

Def 9.8. : Let σ and θ be **substitutions** and $W \subseteq \mathcal{V}_\ell$, we say that a **substitution** σ is **more general** than θ on W (write as $\sigma \leq \theta[W]$), iff there is a **substitution** ρ , such that $\theta = \rho \circ \sigma[W]$, where $\sigma = \rho[W]$, iff $\sigma(X) = \rho(X)$ for all $X \in W$

- The substitution $\sigma = [g(Z)/X, Z/Y]$ is **more general** than $\theta = [g(a)/X, a/Y]$ because there exists $\rho = [a/Z]$ such that:

$$\theta = \rho \circ \sigma$$

This identity $\theta = \rho \circ \sigma$ is verified by applying the **composition** to the variables in the domain:

- $(\rho \circ \sigma)(X) = \rho(\sigma(X)) = \rho(g(Z)) = g(a)$
- $(\rho \circ \sigma)(Y) = \rho(\sigma(Y)) = \rho(Z) = a$

Since the mapping for each variable matches θ , we confirm that θ is a specialization of σ via ρ .

- Likewise, σ is **more general** than $\theta' = [g(g(a))/X, g(a)/Y]$ via $\rho' = [g(a)/Z]$, since:

$$\theta' = \rho' \circ \sigma$$

where $(\rho' \circ \sigma)(X) = g(g(a))$ and $(\rho' \circ \sigma)(Y) = g(a)$.

Def 9.9. MGU: σ is called a **most general unifier (mgu)** of A_1, A_2 , iff it is **minimal** in $U(A_1, A_2)$ **with respect to** the **more general** ordering (\leq) restricted to the variables occurring in the problem: $W = \text{free}(A_1) \cup \text{free}(A_2)$.

Def 9.10. : We call a pair $A =? B$ **solved** in a **unification problem** \mathcal{E} , iff A is a variable X , $\mathcal{E} = X =? A \wedge \mathcal{E}'$, and $X \notin (\text{free}(A) \cup \text{free}(\mathcal{E}'))$. We call a **unification problem** \mathcal{E} a **solved form**, iff all its pairs are **solved**.

Lemma 9.1. **Solved forms** are of the form $X^1 =? B^1 \wedge \dots \wedge X^n =? B^n$ where X^i are distinct and $X^i \notin \text{free}(B^j)$

Def 9.11. \mathcal{E}_σ : Any **substitution** $\sigma = [B^1/X^1], \dots, [B^n/X^n]$ induces a **solved unification problem**

$$\mathcal{E}_\sigma := (X^1 =? B^1 \wedge \dots \wedge X^n =? B^n)$$

Lemma 9.2. If $\mathcal{E} = X^1 =? B^1 \wedge \dots \wedge X^n =? B^n$ is a **solved form**, then \mathcal{E} has the unique **MGU** $\sigma_\epsilon := [B^1/X^1], \dots, [B^n/X^n]$.

Def 9.12. \mathcal{U} : The inference system \mathcal{U} consists of the following **inference rules**:

$$\frac{\mathcal{E} \wedge f(A^1, \dots, A^n) =? f(B^1, \dots, B^n)}{\mathcal{E} \wedge A^1 =? B^1 \wedge \dots \wedge A^n =? B^n} \mathcal{U}_{dec} \quad \frac{\mathcal{E} \wedge A =? A}{\mathcal{E}} \mathcal{U}_{triv}$$

$$\frac{\mathcal{E} \wedge X =? A \quad X \notin \text{free}(A) \quad X \in \text{free}(\mathcal{E})}{[A/X](\mathcal{E} \wedge X =? A)} \mathcal{U}_{elim} \quad \frac{\mathcal{E} \wedge f(X^1, \dots, X^n) =? g(Y^1, \dots, Y^n)}{\perp} \mathcal{U}_\perp$$

Lemma 9.3. \mathcal{U} is **sound**: $\mathcal{E} \vdash_{\mathcal{U}} \mathcal{F}$ implies $U(\mathcal{F}) \subseteq U(\mathcal{E})$

Lemma 9.4. \mathcal{U} is **complete**: $\mathcal{E} \vdash_{\mathcal{U}} \mathcal{F}$ implies $U(\mathcal{E}) \subseteq U(\mathcal{F})$

Lemma 9.5. \mathcal{U} is confluent: the order of derivations does not matter

Corollary 9.6. First-Order **unification** is unitary: i.e. **MGUs** are unique up to **renaming** of **introduced variables**

Lemma 9.7. \mathcal{U} is terminating; any \mathcal{U} -derivation is **finite**

Def 9.13. : We call an equational problem \mathcal{E} **\mathcal{U} -reducible**, iff there is a \mathcal{U} -step $\mathcal{E} \vdash_{\mathcal{U}} \mathcal{F}$ from \mathcal{E}

Lemma 9.8. If \mathcal{E} is **unifiable** but not **solved**, then it is **\mathcal{U} -reducible**

Corollary 9.9. First-Order **unification** is decidable in **PL**¹