Proof. ($\Leftarrow$) Assume that S' is unsatisfiable. Then there exists at least one unsatisfiable formula $\phi \in S'$. Since $S' \subseteq S$, S is also unsatisfiable.

($\Rightarrow$) Let S be unsatisfiable and let N be the set of clauses obtained by Skolemization and CNF transformation of the formulas in S. Clearly $Res^*(N)$ is unsatisfiable. By Theorem 3.10.11, $\perp \in Res^*(N)$, and therefore $\perp \in Res^n(N)$ for some $n \in \mathbb{N}$. Consequently, $\perp$ has a finite resolution proof B of depth$\leq n$. Choose S' as the subset of formulas in S so that the corresponding clauses contain the assumptions (leaves) of B. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\square$

3.11   Orderings

Propositional superposition is based on an ordering on the propositional variables, Section 2.7. The ordering is total and well-founded. Basically, propositional variables correspond to ground atoms in first-order logic. This section generalizes the ideas of the propositional superposition ordering to first-order logic. In first-order logic the ordering has to also consider terms and variables and operations on terms like the application of a substitution.

Definition 3.11.1 (Σ-Operation Compatible Relation)**.** A binary relation $\sqsupset$ over $T(\Sigma, \mathcal{X})$ is called *compatible with Σ-operations,* if $s \sqsupset s'$ implies $f(t_1, \ldots, s, \ldots, t_n) \sqsupset f(t_1, \ldots, s', \ldots, t_n)$ for all $f \in \Omega$ and $s, s', t_i \in T(\Sigma, \mathcal{X})$.

Lemma 3.11.2 (Σ-Operation Compatible Relation)**.** A relation $\sqsupset$ is compatible with Σ-operations iff $s \sqsupset s'$ implies $t[s]_p \sqsupset t[s']_p$ for all $s, s', t \in T(\Sigma, \mathcal{X})$ and $p \in pos(t)$.

   In the literature *compatible with Σ-operations* is sometimes also called *compatible with contexts.*

Definition 3.11.3 (Substitution Stable Relation, Rewrite Relation)**.** A binary relation $\sqsupset$ over $T(\Sigma, \mathcal{X})$ is called *stable under substitutions*, if $s \sqsupset s'$ implies $s\sigma \sqsupset s'\sigma$ for all $s, s' \in T(\Sigma, \mathcal{X})$ and substitutions σ. A binary relation $\sqsupset$ is called a *rewrite relation*, if it is compatible with Σ-operations and stable under substitutions.

   A *rewrite ordering* is then an ordering that is a rewrite relation.

Definition 3.11.4 (Subterm Ordering)**.** The *proper subterm ordering $s > t$* is defined by $s > t$ iff $s|_p = t$ for some position $p \neq \epsilon$ of s.

Definition 3.11.5 (Simplification Ordering)**.** A rewrite ordering $\succ$ over $T(\Sigma, \mathcal{X})$ is called *simplification ordering*, if it enjoys the *subterm property $s \succ t$* implies $s > t$ for all $s, t \in T(\Sigma, \mathcal{X})$ of the same sort.

Definition 3.11.6 (Lexicographical Path Ordering (LPO))**.** Let $\Sigma = (\mathcal{S}, \Omega, \Pi)$ be a signature and let $\succ$ be a strict partial ordering on operator symbols in Ω, called *precedence*. The *lexicographical path ordering $\succ_{lpo}$* on $T(\Sigma, \mathcal{X})$ is defined as follows: if s, t are terms in $T_S(\Sigma, \mathcal{X})$ then $s \succ_{lpo} t$ iff

1. $t = x \in \mathcal{X}$, $x \in vars(s)$ and $s \neq t$ or

2. $s = f(s_1, \ldots, s_n)$, $t = g(t_1, \ldots, t_m)$ and

    (a) $s_i \succeq_{lpo} t$ for some $i \in \{1, \ldots, n\}$ or

    (b) $f \succ g$ and $s \succ_{lpo} t_j$ for every $j \in \{1, \ldots, m\}$ or

    (c) $f = g$, $s \succ_{lpo} t_j$ for every $j \in \{1, \ldots, m\}$ and $(s_1, \ldots, s_n)(\succ_{lpo})_{lex}(t_1, \ldots, t_m)$.

Theorem 3.11.7 (LPO Properties). 1. The LPO is a rewrite ordering.

2. LPO enjoys the subterm property, hence is a simplification ordering.

3. If the precedence $\succ$ is total on Ω then $\succ_{lpo}$ is total on the set of ground terms $T(\Sigma)$.

4. If Ω is finite then $\succ_{lpo}$ is well-founded.

Example 3.11.8. Consider the terms $g(x)$, $g(y)$, $g(g(a))$, $g(b)$, $g(a)$, b, a. With respect to the precedence $g \succ b \succ a$ the ordering on the ground terms is $g(g(a)) \succ_{lpo} g(b) \succ_{lpo} g(a) \succ_{lpo} b \succ_{lpo} a$. The terms $g(x)$ and $g(y)$ are not comparable. Note that the terms $g(g(a))$, $g(b)$, $g(a)$ are all instances of both $g(x)$ and $g(y)$.

With respect to the precedence $b \succ a \succ g$ the ordering on the ground terms is $g(b) \succ_{lpo} b \succ_{lpo} g(g(a)) \succ_{lpo} g(a) \succ_{lpo} a$.

Definition 3.11.9 (The Knuth-Bendix Ordering). Let $\Sigma = (\mathcal{S}, \Omega, \Pi)$ be a finite signature, let $\succ$ be a strict partial ordering *("precedence")* on Ω, let $w : \Omega \cup \mathcal{X} \to \mathbb{R}^+$ be a *weight function*, so that the following admissibility condition is satisfied:

$w(x) = w_0 \in \mathbb{R}^+$ for all variables $x \in \mathcal{X}$; $w(c) \geq w_0$ for all constants $c \in \Omega$.

Then, the weight function w can be extended to terms recursively:

$$w(f(t_1, \ldots, t_n)) = w(f) + \sum_{1 \leq i \leq n} w(t_i)$$

or alternatively

$$\sum w(t) = \sum_{x \in vars(t)} w(x) \cdot \#(x, t) + \sum_{f \in \Omega} w(f) \cdot \#(f, t)$$

where $\#(a, t)$ is the number of occurrences of a in t.

The *Knuth-Bendix ordering* $\succ_{kbo}$ on $T(\Sigma, \mathcal{X})$ induced by $\succ$ and admissible w is defined by: $s \succ_{kbo} t$ iff

1. $\#(x, s) \geq \#(x, t)$ for all variables x and $w(s) > w(t)$, or

2. $\#(x, s) \geq \#(x, t)$ for all variables x, $w(s) = w(t)$, and

    (a) $s = f(s_1, \ldots, s_m)$, $t = g(t_1, \ldots, t_n)$, and $f \succ g$, or

   (b) $s = f(s_1, \ldots, s_m)$, $t = f(t_1, \ldots, t_m)$, and $(s_1, \ldots, s_m)(\succ_{kbo})_{lex}(t_1, \ldots, t_m)$.

Theorem 3.11.10 (KBO Properties).   1. The KBO is a rewrite ordering.

   2. KBO enjoys the subterm property, hence is a simplification ordering.

   3. If the precedence $\succ$ is total on Ω then $\succ_{kbo}$ is total on the set of ground terms $T(\Sigma)$.

   4. If Ω is finite then $\succ_{kbo}$ is well-founded.

   The KBO ordering can be extended to contain unary function symbols with weight zero. This was motivated by completion of the group axioms, see Chapter 4.

Definition 3.11.11 (The Knuth-Bendix Ordering Extended). The additional requirements added to Definition 3.11.9 are

   1. Extend w to $w : \Omega \cup \mathcal{X} \to \mathbb{R}_0^+$

   2. If $w(f) = 0$ for some $f \in \Omega$ with arity$(f) = 1$, then $f \succeq g$ for all $g \in \Omega$.

   3. As a first case to the disjunction of 3.11.9-2.
      (a') $t = x$, $s = f^n(x)$ for some $n \geq 1$

   The LPO ordering as well as the KBO ordering can be extended to atoms in a straightforward way. The precedence $\succ$ is extended to Π. For LPO atoms are then compared according to Definition 3.11.6-2. For KBO the weight function w is also extended to atoms by giving predicates a non-zero positive weight and then atoms are compared according to terms.

   Actually, since atoms are never substituted for variables in first-order logic, an alternative to the above would be to first compare the predicate symbols and let $\succ$ decide the ordering. Only if the atoms share the same predicate symbol, the argument terms are considered, e.g., in a lexicographic way and are then compared with respect to KBO or LPO, respectively.

3.12   First-Order Ground Superposition

Propositional clauses and ground clauses are essentially the same, as long as equational atoms are not considered. This section deals only with ground clauses and recalls mostly the material from Section 2.7 for first-order ground clauses. The main difference is that the atom ordering is more complicated, see Section 3.11. Let N be a possibly infinite set of ground clauses.

Definition 3.12.1 (Ground Clause Ordering). Let $\prec$ be a strict rewrite ordering total on ground terms and ground atoms. Then $\prec$ can be lifted to a total ordering $\prec_L$ on literals by its multiset extension $\prec_{\text{mul}}$ where a positive literal

$P(t_1, \ldots, t_n)$ is mapped to the multiset $\{P(t_1, \ldots, t_n)\}$ and a negative literal $\neg P(t_1, \ldots, t_n)$ to the multiset $\{P(t_1, \ldots, t_n), P(t_1, \ldots, t_n)\}$. The ordering $\prec_L$ is further lifted to a total ordering on clauses $\prec_C$ by considering the multiset extension of $\prec_L$ for clauses.

Proposition 3.12.2 (Properties of the Ground Clause Ordering). 1. The orderings on literals and clauses are total and well-founded.

2. Let C and D be clauses with $P(t_1, \ldots, t_n) = \text{atom}(\max(C))$, $Q(s_1, \ldots, s_m) = \text{atom}(\max(D))$, where $\max(C)$ denotes the maximal literal in C.

   (a) If $Q(s_1, \ldots, s_m) \prec_L P(t_1, \ldots, t_n)$ then $D \prec_C C$.
   (b) If $P(t_1, \ldots, t_n) = Q(s_1, \ldots, s_m)$, $P(t_1, \ldots, t_n)$ occurs negatively in C but only positively in D, then $D \prec_C C$.

Eventually, as I did for propositional logic, I overload $\prec$ with $\prec_L$ and $\prec_C$. So if $\prec$ is applied to literals it denotes $\prec_L$, if it is applied to clauses, it denotes $\prec_C$. Note that $\prec$ is a total ordering on literals and clauses as well. For superposition, inferences are restricted to maximal literals with respect to $\prec$. For a clause set N, I define $N^{\prec C} = \{D \in N \mid D \prec C\}$.

Definition 3.12.3 (Abstract Redundancy). A ground clause C is *redundant* with respect to a set of ground clauses N if $N^{\prec C} \models C$.

Tautologies are redundant. Subsumed clauses are redundant if $\subseteq$ is strict. Duplicate clauses are anyway eliminated quietly because the calculus operates on sets of clauses.

Note that for finite N, and any $C \in N$ redundancy $N^{\prec C} \models C$ can be decided but is as hard as testing unsatisfiability for a clause set N. So the goal is to invent redundancy notions that can be efficiently decided and that are useful.

$\boxed{\text{C}}$

Definition 3.12.4 (Selection Function). The selection function sel maps clauses to one of its negative literals or $\bot$. If $\text{sel}(C) = \neg P(t_1, \ldots, t_n)$ then $\neg P(t_1, \ldots, t_n)$ is called *selected* in C. If $\text{sel}(C) = \bot$ then no literal in C is *selected*.

The selection function is, in addition to the ordering, a further means to restrict superposition inferences. If a negative literal is selected in a clause, any superposition inference must be on the selected literal.

Definition 3.12.5 (Partial Model Construction). Given a clause set N and an ordering $\prec$ we can construct a (partial) model $N_{\mathcal{I}}$ for N inductively as follows:

$$N_C := \bigcup_{D \prec C} \delta_D$$

$$\delta_D := \begin{cases} \{P(t_1, \ldots, t_n)\} & \text{if } D = D' \vee P(t_1, \ldots, t_n), P(t_1, \ldots, t_n) \text{ strictly maximal, no literal} \\ & \qquad \text{selected in } D \text{ and } N_D \not\models D \\ \emptyset & \text{otherwise} \end{cases}$$

$$N_{\mathcal{I}} := \bigcup_{C \in N} \delta_C$$

Clauses C with $\delta_C \neq \emptyset$ are called *productive*.

Proposition 3.12.6 (Propertied of the Model Operator). Some properties of the partial model construction.

1. For every D with $(C \vee \neg P(t_1, \ldots, t_n)) \prec D$ we have $\delta_D \neq \{P(t_1, \ldots, t_n)\}$.

2. If $\delta_C = \{P(t_1, \ldots, t_n)\}$ then $N_C \cup \delta_C \models C$.

3. If $N_C \models D$ and $D \prec C$ then for all C' with $C \prec C'$ we have $N_{C'} \models D$ and in particular $N_\mathcal{I} \models D$.

4. There is no clause C with $P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n) \prec C$ such that $\delta_C = \{P(t_1, \ldots, t_n)\}$.

> **T** Please properly distinguish: N is a set of clauses interpreted as the conjunction of all clauses. $N^{\prec C}$ is of set of clauses from N strictly smaller than C with respect to $\prec$. $N_\mathcal{I}$, N_C are Herbrand interpretations (see Proposition 3.5.3). $N_\mathcal{I}$ is the overall (partial) model for N, whereas N_C is generated from all clauses from N strictly smaller than C.

Superposition Left $(N \uplus \{C_1 \vee P(t_1, \ldots, t_n), C_2 \vee \neg P(t_1, \ldots, t_n)\}) \Rightarrow_{\mathrm{SUP}}$
$(N \cup \{C_1 \vee P(t_1, \ldots, t_n), C_2 \vee \neg P(t_1, \ldots, t_n)\} \cup \{C_1 \vee C_2\})$

where (i) $P(t_1, \ldots, t_n)$ is strictly maximal in $C_1 \vee P(t_1, \ldots, t_n)$ (ii) no literal in $C_1 \vee P(t_1, \ldots, t_n)$ is selected (iii) $\neg P(t_1, \ldots, t_n)$ is maximal and no literal selected in $C_2 \vee \neg P(t_1, \ldots, t_n)$, or $\neg P(t_1, \ldots, t_n)$ is selected in $C_2 \vee \neg P(t_1, \ldots, t_n)$

Factoring $(N \uplus \{C \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n)\}) \Rightarrow_{\mathrm{SUP}}$
$(N \cup \{C \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n)\} \cup \{C \vee P(t_1, \ldots, t_n)\})$

where (i) $P(t_1, \ldots, t_n)$ is maximal in $C \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n)$ (ii) no literal is selected in $C \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n)$

Note that the superposition factoring rule differs from the resolution factoring rule in that it only applies to positive literals.

Definition 3.12.7 (Saturation). A set N of clauses is called *saturated up to redundancy*, if any inference from non-redundant clauses in N yields a redundant clause with respect to N or is contained in N.

Examples for specific redundancy rules that can be efficiently decided are

Subsumption $(N \uplus \{C_1, C_2\}) \Rightarrow_{\mathrm{SUP}} (N \cup \{C_1\})$
provided $C_1 \subset C_2$

Tautology Deletion $(N \uplus \{C \vee P(t_1, \ldots, t_n) \vee \neg P(t_1, \ldots, t_n)\}) \Rightarrow_{\mathrm{SUP}} (N)$

Condensation $(N \uplus \{C_1 \vee L \vee L\}) \Rightarrow_{\mathrm{SUP}} (N \cup \{C_1 \vee L\})$

Subsumption Resolution $\qquad (N \uplus \{C_1 \vee L, C_2 \vee \neg L\}) \Rightarrow_{\mathrm{SUP}} (N \cup \{C_1 \vee L, C_2\})$
where $C_1 \subseteq C_2$

Proposition 3.12.8 (Completeness of the Reduction Rules)**.** All clauses removed by Subsumption, Tautology Deletion, Condensation and Subsumption Resolution are redundant with respect to the kept or added clauses.

Theorem 3.12.9 (Completeness)**.** Let N be a, possibly countably infinite, set of ground clauses. If N is saturated up to redundancy and $\bot \notin N$ then N is satisfiable and $N_{\mathcal{I}} \models N$.

Proof. The proof is by contradiction. So I assume: (i) for any clause D derived by Superposition Left or Factoring from N that D is redundant, i.e., $N^{\prec D} \models D$, (ii) $\bot \notin N$ and (iii) $N_{\mathcal{I}} \not\models N$. Then there is a minimal, with respect to $\prec$, clause $C \vee L \in N$ such that $N_{\mathcal{I}} \not\models C \vee L$ and L is a selected literal in $C \vee L$ or no literal in $C \vee L$ is selected and L is maximal. This clause must exist because $\bot \notin N$.

The clause $C \vee L$ is not redundant. For otherwise, $N^{\prec C \vee L} \models C \vee L$ and hence $N_{\mathcal{I}} \models C \vee L$, because $N_{\mathcal{I}} \models N^{\prec C \vee L}$, a contradiction.

I distinguish the case L is a positive and no literal selected in $C \vee L$ or L is a negative literal. Firstly, assume L is positive, i.e., $L = P(t_1, \ldots, t_n)$ for some ground atom $P(t_1, \ldots, t_n)$. Now if $P(t_1, \ldots, t_n)$ is strictly maximal in $C \vee P(t_1, \ldots, t_n)$ then actually $\delta_{C \vee P} = \{P(t_1, \ldots, t_n)\}$ and hence $N_{\mathcal{I}} \models C \vee P$, a contradiction. So $P(t_1, \ldots, t_n)$ is not strictly maximal. But then actually $C \vee P(t_1, \ldots, t_n)$ has the form $C_1' \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n)$ and Factoring derives $C_1' \vee P(t_1, \ldots, t_n)$ where $(C_1' \vee P(t_1, \ldots, t_n)) \prec (C_1' \vee P(t_1, \ldots, t_n) \vee P(t_1, \ldots, t_n))$. Now $C_1' \vee P(t_1, \ldots, t_n)$ is not redundant, strictly smaller than $C \vee L$, we have $C_1' \vee P(t_1, \ldots, t_n) \in N$ and $N_{\mathcal{I}} \not\models C_1' \vee P(t_1, \ldots, t_n)$, a contradiction against the choice that $C \vee L$ is minimal.

Secondly, let us assume L is negative, i.e., $L = \neg P(t_1, \ldots, t_n)$ for some ground atom $P(t_1, \ldots, t_n)$. Then, since $N_{\mathcal{I}} \not\models C \vee \neg P(t_1, \ldots, t_n)$ we know $P(t_1, \ldots, t_n) \in N_{\mathcal{I}}$. So there is a clause $D \vee P(t_1, \ldots, t_n) \in N$ where $\delta_{D \vee P(t_1, \ldots, t_n)} = \{P(t_1, \ldots, t_n)\}$ and $P(t_1, \ldots, t_n)$ is strictly maximal in $D \vee P(t_1, \ldots, t_n)$ and $(D \vee P(t_1, \ldots, t_n)) \prec (C \vee \neg P(t_1, \ldots, t_n))$. So Superposition Left derives $C \vee D$ where $(C \vee D) \prec (C \vee \neg P(t_1, \ldots, t_n))$. The derived clause $C \vee D$ cannot be redundant, because for otherwise either $N^{\prec D \vee P(t_1, \ldots, t_n)} \models D \vee P(t_1, \ldots, t_n)$ or $N^{\prec C \vee \neg P(t_1, \ldots, t_n)} \models C \vee \neg P(t_1, \ldots, t_n)$. So $C \vee D \in N$ and $N_{\mathcal{I}} \not\models C \vee D$, a contradiction against the choice that $C \vee L$ is the minimal false clause. $\qquad \square$

So the proof actually tells us that at any point in time we need only to consider either a superposition left inference between a minimal false clause and a productive clause or a factoring inference on a minimal false clause.

Theorem 3.12.10 (Compactness of First-Order Logic)**.** Let N be a, possibly countably infinite, set of first-order logic ground clauses. Then N is unsatisfiable iff there is a finite subset $N' \subseteq N$ such that N' is unsatisfiable.

Proof. If N is unsatisfiable, saturation via superposition generates $\bot$. So there is an i such that $N \Rightarrow^i_{\text{SUP}} N'$ and $\bot \in N'$. The clause $\bot$ is the result of at most i-many superposition inferences, reductions on clauses $\{C_1, \ldots, C_n\} \subseteq N$. Superposition is sound, so $\{C_1, \ldots, C_n\}$ is a finite, unsatisfiable subset of N. $\square$

Corollary 3.12.11 (Compactness of First-Order Logic: Classical)**.** A set N of clauses is satisfiable iff all finite subsets of N are satisfiable.

Theorem 3.12.12 (Soundness and Completeness of Ground Superposition)**.** A first-order Σ-sentence ϕ is valid iff there exists a ground superposition refutation for $\text{grd}(\Sigma, \text{cnf}(\neg\phi))$.

Proof. A first-order sentence ϕ is valid iff $\neg\phi$ is unsatisfiable iff $\text{acnf}(\neg\phi)$ is unsatisfiable iff $\text{grd}(\Sigma, \text{cnf}(\neg\phi))$ is unsatisfiable iff superposition provides a refutation of $\text{grd}(\Sigma, \text{cnf}(\neg\phi))$. $\square$

Theorem 3.12.13 (Semi-Decidability of First-Order Logic by Ground Superposition)**.** If a first-order Σ-sentence ϕ is valid then a ground superposition refutation can be computed.

Proof. In a fair way enumerate $\text{grd}(\Sigma, \text{acnf}(\neg\phi))$ and perform superposition inference steps. The enumeration can, e.g., be done by considering Herbrand terms of increasing size. $\square$

Example 3.12.14 (Ground Superposition)**.** Consider the below clauses 1-4 and superposition refutation with respect a KBO with precedence $P \succ Q \succ g \succ f \succ c \succ b \succ a$ where the weight function w returns 1 for all signature symbols. Maximal literals are marked with a *.

$$
\begin{array}{lll}
1. & \neg P(f(c))^* \vee \neg P(f(c))^* \vee Q(b) & \text{(Input)} \\
2. & P(f(c))^* \vee Q(b) & \text{(Input)} \\
3. & \neg P(g(b,c))^* \vee \neg Q(b) & \text{(Input)} \\
4. & P(g(b,c))^* & \text{(Input)} \\
5. & \neg P(f(c))^* \vee Q(b) & \text{(Cond(1))} \\
6. & Q(b)^* \vee Q(b)^* & \text{(Sup(5,2))} \\
7. & Q(b)^* & \text{(Fact(6))} \\
8. & \neg Q(b)^* & \text{(Sup(3,4))} \\
10. & \bot & \text{(Sup(8,7))}
\end{array}
$$

Note that clause 5 cannot be derived by Factoring whereas clause 7 can also be derived by Condensation. Clause 8 is also the result of a Subsumption Resolution application to clauses 3, 4.

Theorem 3.12.15 (Craig Theorem [18])**.** Let ϕ and ψ be two propositional (first-order ground) formulas so that $\phi \models \psi$. Then there exists a formula χ (called the *interpolant* for $\phi \models \psi$), so that χ contains only propositional variables (first-order signature symbols) occurring both in ϕ and in ψ so that $\phi \models \chi$ and $\chi \models \psi$.

Proof. Translate ϕ and $\neg\psi$ into CNF. let N and M, respectively, denote the resulting clause set. Choose an atom ordering $\succ$ for which the propositional variables that occur in ϕ but not in ψ are maximal. Saturate N into N^* w.r.t. $Sup_{sel}^{\succ}$ with an empty selection function sel. Then saturate $N^* \cup M$ w.r.t. $Sup_{sel}^{\succ}$ to derive $\bot$. As N^* is already saturated, due to the ordering restrictions only inferences need to be considered where premises, if they are from N^*, only contain symbols that also occur in ψ. The conjunction of these premises is an interpolant χ. The theorem also holds for first-order formulas. For universal formulas the above proof can be easily extended. In the general case, a proof based on superposition technology is more complicated because of Skolemization. $\quad\square$

3.13 First-Order Superposition

Now the result for ground superposition are lifted to superposition on first-order clauses with variables, still without equality. The completeness proof of ground superposition above talks about (strictly) maximal literals of *ground* clauses. The non-ground calculus considers those literals that correspond to (strictly) maximal literals of ground instances.

The used ordering is exactly the ordering of Definition 3.12.1 where clauses with variables are projected to their ground instances for ordering computations.

Definition 3.13.1 (Maximal Literal). A literal L is called *maximal* in a clause C if and only if there exists a grounding substitution σ so that $L\sigma$ is maximal in $C\sigma$, i.e., there is no different $L' \in C$: $L\sigma \prec L'\sigma$. The literal L is called *strictly maximal* if there is no different $L' \in C$ such that $L\sigma \preceq L'\sigma$.

Note that the orderings KBO and LPO cannot be total on atoms with variables, because they are stable under substitutions. Therefore, maximality can also be defined on the basis of absence of greater literals. A literal L is called *maximal* in a clause C if $L \not\prec L'$ for all other literals $L' \in C$. It is called *strictly maximal* in a clause C if $L \not\preceq L'$ for all other literals $L' \in C$.

Superposition Left $\quad (N \uplus \{C_1 \vee P(t_1,\ldots,t_n), C_2 \vee \neg P(s_1,\ldots,s_n)\}) \Rightarrow_{\text{SUP}}$
$(N \cup \{C_1 \vee P(t_1,\ldots,t_n), C_2 \vee \neg P(s_1,\ldots,s_n)\} \cup \{(C_1 \vee C_2)\sigma\})$
where (i) $P(t_1,\ldots,t_n)\sigma$ is strictly maximal in $(C_1 \vee P(t_1,\ldots,t_n))\sigma$ (ii) no literal in $C_1 \vee P(t_1,\ldots,t_n)$ is selected (iii) $\neg P(s_1,\ldots,s_n)\sigma$ is maximal and no literal selected in $(C_2 \vee \neg P(s_1,\ldots,s_n))\sigma$, or $\neg P(s_1,\ldots,s_n)$ is selected in $(C_2 \vee \neg P(s_1,\ldots,s_n))\sigma$ (iv) σ is the mgu of $P(t_1,\ldots,t_n)$ and $P(s_1,\ldots,s_n)$

Factoring $\quad (N \uplus \{C \vee P(t_1,\ldots,t_n) \vee P(s_1,\ldots,s_n)\}) \Rightarrow_{\text{SUP}}$
$(N \cup \{C \vee P(t_1,\ldots,t_n) \vee P(s_1,\ldots,s_n)\} \cup \{(C \vee P(t_1,\ldots,t_n))\sigma\})$
where (i) $P(t_1,\ldots,t_n)\sigma$ is maximal in $(C \vee P(t_1,\ldots,t_n) \vee P(s_1,\ldots,s_n))\sigma$ (ii) no literal is selected in $C \vee P(t_1,\ldots,t_n) \vee P(s_1,\ldots,s_n)$ (iii) σ is the mgu of $P(t_1,\ldots,t_n)$ and $P(s_1,\ldots,s_n)$