LOGICS EXERCISE

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Submission of homework: Before tutorial on 24.04.2018. Until further notice, homework has to be submitted in groups of two students.

Exercise 2.1. [Resolution Completeness]

1. Does $F \models C$ imply $F \vdash_{\text{Res}} C$? Proof or counterexample!
2. Can you prove $F \models C$ by resolution?

Solution:
Resolution can be used to prove that $F \models \bot$. From the lecture notes: F unsatisfiable iff $F \vdash_{\text{Res}} \Box$.

1. Counterexample: $F = \{\}, C = \{\{A, \neg A\}\}$
2. $F \models C$
   iff $\models \neg F \vee C$
   iff $\neg F \vee C$ tautology
   iff $\neg(\neg F \vee C)$ unsatisfiable
   iff $\neg(\neg F \vee C) \vdash_{\text{Res}} \Box$

Exercise 2.2. [Resolution of Horn-Clauses]
Can the resolvent of two Horn-clauses be a non-Horn clause?

Solution:
No. Proof: Let C_1, C_2 be two Horn clauses. Both of them have at most one positive literal. Without loss of generality, let A_i be the positive literal occuring in C_1. Hence, $\neg A_i$ occurs in C_2. From the Horn clause property, we get that there is no other positive literal in C_1 and at most one in C_2. The resolvent is $C' = (C_1 - \{A_i\}) \cup (C_2 - \{\neg A_i\})$. We count the positive literals: None in $(C_1 - \{A_i\})$ and at most one in $(C_2 - \{\neg A_i\})$. Hence, at most one positive literal in C'.

Exercise 2.3. [Optimizing Resolution]
We call a clause C *trivially true* if $A_i \in C$ and $\neg A_i \in C$ for some atom A_i. Show that the resolution algorithm remains complete if it does not consider trivially true clauses for resolution.

Solution:
Completeness: If F unsatisfiable, then $F \vdash_{\text{Res'}} \Box$.

First we prove a lemma: If F is unsatisfiable and contains a trivially true clause C, then $F' = F - C$ is still unsatisfiable. Proof by contraposition. Assume $F - C$ is satisfiable. Because C is trivially satisfiable, $(F - C) \cup C = F$ is satisfiable. It follows that we can construct a F' that contains no trivial clauses.

Assume that F is unsatisfiable. We modify the completeness proof of resolution. Recall that that proof proceeds by induction on the number of atomic formulas in F. We strengthen the induction by mandating that F contains no trivially true clauses. Initially, this is guaranteed by the lemma. If F is an unsatisfiable set of clauses containing $n + 1$ atomic formulas, we construct F_0 and F_1 by setting A_{n+1} to 0 or 1, respectively. Both F_0 and F_1 are unsatisfiable. Also, neither F_0 nor F_1 contain trivial clauses. By induction hypothesis, we can obtain resolution proofs such that $F_0 \vdash_{\text{Res'}} \Box$ and $F_1 \vdash_{\text{Res'}} \Box$. Constructing the new resolution proof for F introduces no new trivial clauses.

Exercise 2.4. [Finite Axiomatization]
Let M_0 and M be sets of formulas. M_0 is called *axiom schema* for M, iff for all assignments $\mathcal{A}$: $\mathcal{A} \models M_0$ iff $\mathcal{A} \models M$.

A set M is called *finitely axiomatized* iff there is a finite axiom schema for M.

1. Are all sets of formulas finitely axiomatized? Proof or counterexample!
2. Let $M = (F_i)_{i \in \mathbb{N}}$ be a sequence of formulas, such that for all i: $F_{i+1} \models F_i$, and not $F_i \models F_{i+1}$. Is M finitely axiomatized?

Solution:

1. Counterexample: $M = \{A_1, A_1 \wedge A_2, A_1 \wedge A_2 \wedge A_3, \ldots\}$. Assume there is a finite axiom schema M_0. M_0 can only contain finitely many atoms. Let $\mathcal{A}$ be an assignment that maps all A_i in M_0 to 1, but all other A_i to 0. Hence, $\mathcal{A} \models M_0$ but not $\mathcal{A} \models M$.
2. The same counterexample as above works here.

Exercise 2.5. **[Compactness Theorem]**
Suppose every finite subset of S is satisfiable. Show that then

every finite subset of $S \cup \{F\}$ is satisfiable or
every finite subset of $S \cup \{\neg F\}$ is satisfiable

for any formula F.

Solution:
Proof by contradiction. Suppose $S \cup \{F\}$ has an unsatisfiable subset M and $S \cup \{\neg F\}$ has an unsatisfiable subset L. We can assume that $M = M' \cup \{F\}$ and $L = L' \cup \{\neg F\}$ for some M', L' where $M' \subseteq S$ and $L' \subseteq S$ because every subset of S is satisfiable. We additionally know that $M' \cup L'$ is satisfiable by assumption. Consider the sets

$$M' \cup L' \cup \{F\} \qquad \text{and} \qquad M' \cup L' \cup \{\neg F\}$$

Then one of them has to be satisfiable. (Let $\mathcal{A}$ with $\mathcal{A} \models M' \cup L'$. Then either $\mathcal{A} \models F$ or $\mathcal{A} \not\models F$. That is, $\mathcal{A} \models F$ or $\mathcal{A} \models \neg F$.) This directly implies that either M or L is satisfiable, a contradiction.

Homework 2.1. **[Resolution]** (4 points)

Use the resolution procedure to decide if the following formulas are satisfiable. Show your work (by giving the corresponding DAG or linear derivation)!

1. $(A_1 \vee A_2 \vee \neg A_3) \wedge \neg A_1 \wedge (A_1 \vee A_2 \vee A_3) \wedge (A_1 \vee \neg A_2)$
2. $(\neg A_1 \vee A_2) \wedge (\neg A_2 \vee A_3) \wedge (A_1 \vee \neg A_3) \wedge (A_1 \vee A_2 \vee A_3)$

Homework 2.2. **[Negative Resolution]** (6 points)

We call a clause C *negative* if it only contains negative clauses. Show that resolution remains complete if it only resolves two clauses if one of them is negative.

Homework 2.3. **[Satisfiability]** (5 points)

Check the following formulas for satisfiability using one of the algorithms seen in the lecture:

1. $(A \vee \neg B \vee \neg D \vee \neg E) \wedge (\neg B \vee C) \wedge B \wedge (\neg C \vee D) \wedge (\neg D \vee E)$
2. $\neg(((A \to B) \wedge (B \to A)) \to (A \leftrightarrow B))$
3. $(A \to E) \wedge (B \to \bot) \wedge (C \to B) \wedge (\top \to A) \wedge (A \wedge B \to C) \wedge (C \to D)$

Show your work! Remember to give a model for satisfiable formulas.

Homework 2.4. **[Application of the Compactness Theorem]** (5 points)
A finitely branching tree has the following structure:

- There is exactly one root node.
- Every node has a finite number of children.

We assign the root node the *level* 0 and the children of a node at level n the level $n + 1$. Let T_n denote the set of all nodes at level n, and T the set of all nodes, i.e. $T = \bigcup_{n \in \mathbb{N}} T_n$. Let P_t for $t \in T$ be the set of parent nodes of a node, i.e. t is a child (or grand-child, ...) of all $t' \in P_t$. A path is a sequence of connected nodes, starting from the root node.

Prove the following lemma using the compactness theorem: Every countably infinite, finitely branching tree has an infinite path.

Hint: Use the following template for the proof.

1. Fix a set of tree nodes T. This set is (countably) infinite. You can assume that the sets T_n and the sets P_t are given.
2. For each node $t \in T$, let A_t be an atomic formula. If an assignment $\mathcal{A}$ makes A_t true, the node t is part of the path.
3. Define a set of propositions S that together guarantee the existence of an infinite path. That set is composed of three subsets:
   (a) For each level $n \in \mathbb{N}$, a node $t \in T_n$ is part of the path.
   (b) If a node t is part of the path, so are all of its parent nodes $t' \in P_t$.
   (c) For each level $n \in \mathbb{N}$, there is at most one node of level n part of the path.
4. Show that any finite subset of $S' \subseteq S$ is satisfiable by constructing an assignment such that $\mathcal{A}_{S'} \models S'$. Consider the largest n for which a proposition from subset (a) is contained in S'.
5. Hence, S is satisfiable. Show that a model $\mathcal{A} \models S$ represents an infinite path in T.