Announcements / Reminders Please follow the Week 08 To Do List instructions Illinois Institute of Technology	Plan for Today Predicate / First-Order Logic Minois Institute of Technology 3	Proof by Resolution The process of proving by resolution is as follows: A. Formalize the problem: "English to Predicate Logic" B. Derive KB A A Q [in general: NOT(Some Sentence)] C. Convert KB A A Q into CNF ("standardized") form D. Apply resolution rule to resulting clauses. New clause will be generated (add them to the set if not already present) E. Repeat (D) until: a. no new clause can be added (KB does NOT entail Q) b. last two clauses resolve to yield the empty clause (KB entails Q) entails Q)	Proof by Resolution The process of proving by resolution is as follows: A. Formalize the problem: "English to Predicate Logic" B. Negate the input statement/claim ℂ to obtain ¬ ℂ C. Convert ¬ ℂ into CNF ("standardized") form s. D. Apply resolution rule to resulting clauses. New clauses will be generated (add them to the set if not already present) E. Repeat (D) until: a. no new clause can be added (ℂ is false) b. last two clauses resolve to yield the empty clause (ℂ is true)
Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge: 1. Eliminate all equivalences ⇔ and implications ⇒ 2. Reduce the scope of all ¬to single term (De Morgan) 3. Make all variable names unique (standardize apart) 4. Move quantifiers left (convert to prenex normal form) 5. Eliminate Existential quantifiers (skolemization) 6. Eliminate Universal quantifiers 7. Convert to conjunction of disjuncts 8. Create separate clause for each conjunct	Converting FOL to CNF: Example 1 Original sentence S: $\forall w.([P_i(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x. (\exists y. (P_a(x, y) \Rightarrow P_4(w, x))])) \wedge [\forall w. (P_3(w))]$ Illinois Institute of Technology 7	Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge: 1. Eliminate all equivalences ⇔ and implications ⇒ 2. Reduce the scope of all ¬to single term (De Morgan) 3. Make all variable names unique (standardize apart) 4. Move quantifiers left (convert to prenex normal form) 5. Eliminate Existential quantifiers (skolemization) 6. Eliminate Universal quantifiers 7. Convert to conjunction of disjuncts 8. Create separate clause for each conjunct	Converting FOL to CNF: Example 1 Original sentence S: $ \forall w \ (P_1(w) \lor P_2(w) \Rightarrow P_3(w)] \lor [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x))]), \land [\forall w \ (P_3(w))] $ By Implication Law $(p \Rightarrow q \equiv \neg p \lor q)$: $ \forall w \ ([\underline{P_1(w) \lor P_2(w) \Rightarrow P_2(w)}] \lor [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x))]), \land [\forall w \ (P_3(w))] $ becomes: $ \forall w \ ([\underline{-P_1(w) \lor P_2(w)}] \lor [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x))]), \land [\forall w \ (P_3(w))] $ By Implication Law $(p \Rightarrow q \equiv \neg p \lor q)$: $ \forall w \ ([-P_1(w) \lor P_2(w)) \lor P_3(w)] \lor [\exists x \ (\exists y \ (\underline{P_2(x,x)}) \Rightarrow \underline{P_2(w,x)})]), \land [\forall w \ (P_3(w))] $ becomes: $ \forall w \ ([-P_1(w) \lor P_2(w)) \lor P_3(w)] \lor [\exists x \ (\exists y \ (\underline{-P_2(x,x)}) \Rightarrow \underline{P_2(w,x)})]), \land [\forall w \ (P_3(w))] $ Hilinois institute of Technology
Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge: 1. Eliminate all equivalences ⇔ and implications ⇒ 2. Reduce the scope of all ¬ to single term (De Morgan) 3. Make all variable names unique (standardize apart) 4. Move quantifiers left (convert to prenex normal form) 5. Eliminate Existential quantifiers (skolemization) 6. Eliminate Universal quantifiers 7. Convert to conjunction of disjuncts 8. Create separate clause for each conjunct	 Converting FOL to CNF: Example 1 Original sentence S: ∀w (IP (w) ∨ P₂(w) ⇒ P₃(w)] ∨ [∃x (∃y (P₀(x, y) ⇒ P₄(w, x)))) ∧ [∀w (P₃(w))] By De Morgan's Law (¬(p ∨ q) ≡ ¬p ∧ ¬q): ∀w ([¬P₂(w) ∨ P₂(w)) ∨ [∃x (∃y (¬P₀(x, y) ∨ P₄(w, x))]) ∧ [∀w (P₃(w))] becomes: ∀w (([¬P₂(w) ∧ ¬P₂(w)) ∨ [∃x (∃y (¬P₀(x, y) ∨ P₄(w, x))]) ∧ [∀w (P₃(w))] Ww (([¬P₂(w) ∧ ¬P₂(w)) ∨ [∃x (∃y (¬P₀(x, y) ∨ P₄(w, x))]) ∧ [∀w (P₃(w))] Illinois Institute of Technology 	Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge: 1. Eliminate all equivalences ⇔ and implications ⇒ 2. Reduce the scope of all ¬ to single term (De Morgan) 3. Make all variable names unique (standardize apart) 4. Move quantifiers left (convert to prenex normal form) 5. Eliminate Existential quantifiers (skolemization) 6. Eliminate Universal quantifiers 7. Convert to conjunction of disjuncts 8. Create separate clause for each conjunct	Converting FOL to CNF: Example 1 Original sentence S: $\forall \mathbf{w} (P_{1}(\mathbf{w}) \vee P_{2}(\mathbf{w}) = P_{3}(\mathbf{w})] \vee [\exists x (\exists y (P_{6}(x, y) \Rightarrow P_{4}(\mathbf{w}, x))))) \wedge [\forall \mathbf{w} (P_{3}(\mathbf{w}))]$ Variable w (w and w) is bound to two different quantifiers: $\forall \mathbf{w} ([\neg P_{1}(\mathbf{w}) \vee P_{2}(\mathbf{w})) \vee P_{3}(\mathbf{w})] \vee [\exists x (\exists y (\neg P_{6}(x, y) \vee P_{4}(\mathbf{w}, x)))) \wedge [\forall \mathbf{w} (P_{3}(\mathbf{w}))]$ Replace w with z and the sentence S becomes: $\forall \mathbf{w} ([(\neg P_{1}(\mathbf{w}) \wedge \neg P_{3}(\mathbf{w})) \vee P_{3}(\mathbf{w})] \vee [\exists x (\exists y (\neg P_{6}(x, y) \vee P_{4}(\mathbf{w}, x)))) \wedge [\forall x (P_{5}(x))]$ $\forall \mathbf{w} ([(\neg P_{1}(\mathbf{w}) \wedge \neg P_{3}(\mathbf{w})) \vee P_{3}(\mathbf{w})] \vee [\exists x (\exists y (\neg P_{6}(x, y) \vee P_{4}(\mathbf{w}, x)))) \wedge [\forall x (P_{5}(x))]$ 12 Illinois Institute of Technology
rst-Order) Logic to CNF iers are a challenge: valences ⇔ and implications ⇒ of all ¬ to single term (De Morgan) names unique (standardize apart) left (convert to prenex normal form ial quantifiers (skolemization) al quantifiers ction of disjuncts ause for each conjunct	-OL to CNF: Example 1 -OL to CNF: Example 1	rst-Order) Logic to CNF iers are a challenge: Alences ⇔ and implications ⇒ of all ¬ to single term (De Morgan) names unique (standardize apart) left (convert to prenex normal form ial quantifiers (skolemization) al quantifiers ction of disjuncts ause for each conjunct	FOL to CNF: Example 1 Solution (P ₄ (x, y) = P ₄ (w, x)))) \wedge [\forall w (P ₄ (w))) $ \vee$ [\exists x [\exists y (P ₆ (x, y) = P ₄ (w, x))))) \wedge [\forall w (P ₄ (w)) $ \vee$ [\forall p (\forall x $)$] \vee [\forall p (\forall x

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4. Move quantifiers left (convert to prenex normal form) $\forall w \; ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \; (\exists y \; (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall w \; (P_5(w))]$ Predicate (First-Order) Logic to CNF $\forall w \; ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \; (\exists y \; (P_6(x, \, y) \Rightarrow P_4(w, \, x)))]) \wedge [\forall z \; (P_2(P_3(z))]$ Move quantifiers left (convert to prenex normal form $([(\neg P_1(w) \land \neg P_2(w)) \lor P_3(w)] \lor [(\neg P_6(f(w), g(w)) \lor P_4(w, f(w)))]) \land [(P_5(z))]$ Reduce the scope of all ¬ to single term (De Morgan) Reduce the scope of all ¬ to single term (De Morgan) 3. Make all variable names unique (standardize apart) Converting FOL to CNF: Example Converting FOL to CNF: Example Eliminate all equivalences ⇔ and implications ⇒ By Distributive Law (p \vee (q \wedge r) \Leftrightarrow (p \vee q) \wedge (p \vee r)): 5. Eliminate Existential quantifiers (skolemization) Eliminate Existential quantifiers (skolemization) By Associative Law $((p \lor q) \lor r \Leftrightarrow p \lor (q \lor r))$: 8. Create separate clause for each conjunct Variables and quantifiers are a challenge: $(A \lor C) \land (B \lor C)) \land [(P_5(z))]$ $([A \wedge B] \vee [C]) \wedge [(P_5(z))]$ Convert to conjunction of disjuncts Eliminate Universal quantifiers $C \equiv (\neg P_6(f(w), g(w)) \lor P_4(w, f(w)))$ Illinois Institute of Technology Illinois Institute of Technology llinois Institute of Technology Original sentence 5: Original sentence S: $A \equiv (P_3(\mathbf{w}) \vee \neg P_1(\mathbf{w}))$ $B \equiv (P_3(\mathbf{w}) \lor \neg P_2(\mathbf{w}))$ becomes: secomes: where: $\forall w \forall z \ ([(-P_1(w) \land -P_2(w)) \lor P_3(w)] \lor [(-P_1(w), \underline{e(w)}) \lor P_4(w, f(w)))]) \land [(P_5(z))]$ $\forall w \exists y \forall z \ ([(-P_1(w) \land -P_2(w)) \lor P_3(w)] \lor [(-P_k(f(w), v) \lor P_k(w, f(w)))]) \land [(P_3(z))]$ $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\ \forall w \ (P_5(w))]$ $\forall w \; ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \; (\exists y \; (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall w \; (P_5(w))]$ $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x, \, y) \Rightarrow P_4(w, \, x)))]) \wedge [\forall z \ (P_3(z))]$ Predicate (First-Order) Logic to CNF 4. Move quantifiers left (convert to prenex normal form) Quantified variable y was replaced with Skolem function $([(P_3(w) \vee \neg P_1(w)) \wedge (P_3(w) \vee \neg P_2(w))] \vee [(\neg P_6(f(w), g(w)) \vee P_4(w, f(w)))]) \wedge [(P_3(w)) \vee P_4(w, f(w))]) \wedge [(P_3(w)) \vee P_4(w, f(w))] \wedge [(P_3(w)) \vee P_4(w)] \wedge [(P_3(w)) \vee P_4($ Reduce the scope of all ¬ to single term (De Morgan) Converting FOL to CNF: Example 1 Now: remove $\exists y$ and replace y with a Skolem function: Make all variable names unique (standardize apart) Converting FOL to CNF: Example Converting FOL to CNF: Example Eliminate all equivalences ⇔ and implications ⇒ Eliminate Existential quantifiers (skolemization) $(P_3(w) \vee \neg P_1(w) \vee \neg P_6(f(w),\,g(w)) \vee P_4(w,\,f(w))))$ Convert to conjunction of disjuncts (CNF) Create separate clause for each conjunct $g(\mathbf{w})$. Existential quantifier $\exists y$ was removed Variables and quantifiers are a challenge: $([A \land B] \lor [C]) \land [(P_s(z))]$ We obtained sentence S in CNF form: **Eliminate Universal quantifiers** Let's make some substitutions: so the sentence becomes: $\mathbb{C} \equiv (\neg P_6(f(w), g(w)) \lor P_4(w, f(w)))$ Illinois Institute of Technology Illinois Institute of Technology Illinois Institute of Technology Original sentence S: Original sentence 5: Original sentence S: $A \equiv (P_3(\mathbf{w}) \vee \neg P_1(\mathbf{w}))$ $B \equiv (P_3(\mathbf{w}) \vee \neg P_2(\mathbf{w}))$ becomes: 26 $\forall w \exists y \forall Z \; ([(-P_1(w) \land \neg P_2(w)) \lor P_3(w)] \lor [(\neg P_{\underline{A}}(f(w), \underline{v}) \lor \underline{P_{\underline{A}}(w, f(w))})]) \land [(P_5(Z))]$ $\forall w \ \underline{\exists x} \ \exists y \ \forall z \ ([(\neg P_1(w) \land \neg P_2(w)) \lor P_3(w)] \lor [(\neg P_2(x, y) \lor \underline{P_1(w, x)})]) \land [(P_3(z))]$ $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall w \ (P_3(w))]$ purposes only. Equivalence is lost, but we can still use the $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall w \ (P_5(w))]$ $\frac{([(P_{\underline{1}}(w) \vee \neg P_{\underline{1}}(w)) \wedge (P_{\underline{1}}(w) \vee \neg P_{\underline{1}}(w)) \vee [(\neg P_{\delta}(f(w), g(w)) \vee P_{4}(w, f(w)))]) \wedge [(P_{\underline{1}}(w) \vee \neg P_{\underline{1}}(w)] \vee P_{\underline{1}}(w)])]) \wedge [(P_{\underline{1}}(w) \vee \neg P_{\underline{1}}(w)) \vee P_{\underline{1}}(w)]) \rangle}{[(P_{\underline{1}}(w))]}$ $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall z \ (P_5(z))]$ Quantified variable x was replaced with Skolem function $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall z \ (P_2(z))]$ $([P_{\underline{3}(\mathbf{w})} \vee (\neg P_{\underline{1}(\mathbf{w})} \wedge \neg P_{\underline{2}(\mathbf{w})})] \vee [(\neg P_{6}(f(\mathbf{w}),\,g(\mathbf{w})) \vee P_{4}(\mathbf{w},\,f(\mathbf{w})))]) \wedge [(P_{5}(z))]$ Let's start with $\exists x$ and replace x with a Skolem function: $([(\neg P_1(w) \land \neg P_2(w)) \lor P_3(w)] \lor [(\neg P_6(f(w), g(w)) \lor P_4(w, f(w)))]) \land [(P_5(z))]$ $(((P_3(w) \vee \neg P_1(w)) \vee (\neg P_6(f(w), g(w)) \vee P_4(w, f(w)))) \wedge ((P_3(w) \vee \neg P_2(w)) \vee (P_3(w) \vee P_2(w$ We are "dropping" universal quantifiers for inferential Converting FOL to CNF: Example By Distributive Law (p \vee (q \wedge r) \Leftrightarrow (p \vee q) \wedge (p \vee r)): $.\left(P_{3}(w) \lor \neg P_{2}(w) \lor \neg P_{6}(f(w),\,g(w)) \lor P_{4}(w,\,f(w))\right))$ $(P_i(w) \vee \neg P_i(w) \vee \neg P_k(f(w),\,g(w)) \vee P_4(w,\,f(w))))$ $(\neg P_6(f(w),\,g(w)) \vee P_4(w,\,f(w))))) \wedge [(P_5(z))]$ $f(\mathbf{w})$. Existential quantifier $\exists x$ was removed. We can simply "drop" universal quantifiers: We can remove some parentheses: remaining sentence to infer. llinois Institute of Technology linois Institute of Technolog nois Institute of Technolog Original sentence S: Original sentence S: Original sentence S: Original sentence S: becomes: becomes: pecomes: pecomes

Converting FOL to CNF: Example Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge:

- Eliminate all equivalences ⇔ and implications ⇒
- 3. Make all variable names unique (standardize apart)

- **Eliminate Universal quantifiers**

Remaining quantified variables are universally quantified:

 $\forall w \left(\left[P_1(w) \vee P_2(w) \Rightarrow P_3(w) \right] \vee \left[\exists x \left(\exists y \left(P_6(x,y) \Rightarrow P_4(w,x) \right) \right) \right] \wedge \left[\forall z \left(P_3(z) \right) \right]$

 $\forall w \forall z \ ([(\neg P_1(w) \land \neg P_2(w)) \lor P_3(w)] \lor [(\neg P_6(f(w), g(w)) \lor P_4(w, f(w)))]) \land [(P_5(z))]$

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 $\forall w \ ([P_1(w) \lor P_2(w) \Rightarrow P_3(w)] \lor [\exists x \ (\exists y \ (P_6(x,y) \Rightarrow P_4(w,x)))]) \land [\forall w \ (P_5(w))]]$ Converting FOL to CNF: Example 1

 $\overline{([P_{\underline{1}}(\underline{w}) \vee (\neg P_{\underline{1}}(\underline{w}) \wedge \neg P_{\underline{2}}(\underline{w})]}] \vee [(\neg P_{6}(f(w),\,g(w)) \vee P_{4}(w,\,f(w))]]) \wedge [(P_{5}(Z))]}$ By Associative Law $((p \lor q) \lor r \Leftrightarrow p \lor (q \lor r))$: pecomes:

 $([\underline{P_{\underline{3}}(w) \vee (\neg P_{\underline{1}}(w) \wedge \neg P_{\underline{2}}(w))}] \vee [(\neg P_{6}(f(w), g(w)) \vee P_{4}(w, f(w)))]) \wedge [(P_{5}(z))]$

 $([P_3(w) \vee (\neg P_1(w) \wedge \neg P_2(w))] \vee [(\neg P_6(f(w), \, g(w)) \vee P_4(w, \, f(w)))]) \wedge [(P_3(z))]$

where:

 $\forall w \ ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \ (\exists y \ (P_6(x, \, y) \Rightarrow P_4(w, \, x)))]) \wedge [\forall w \ (P_5(w))]$

Original sentence S:

Remove substitutions:

becomes:

Converting FOL to CNF: Example 1

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 $\frac{(((P_3(w) \vee -P_1(w)) \vee (-P_0(f(w),g(w)) \vee P_4(w,f(w))))) \wedge ((P_3(w) \vee -P_2(w)) \vee}{(-P_0(f(w),g(w)) \vee P_4(w,f(w))))) \wedge [(P_3(z))] }$

 $A \equiv (P_3(\mathbf{w}) \vee \neg P_1(\mathbf{w}))$

Converting FOL to CNF: Example 1 $C \equiv (\neg P_6(f(\mathbf{w}), g(\mathbf{w})) \lor P_4(\mathbf{w}, f(\mathbf{w})))$ Illinois Institute of Technolog $B \equiv (P_3(\mathbf{w}) \vee \neg P_2(\mathbf{w}))$

 $\forall w \; ([P_1(w) \vee P_2(w) \Rightarrow P_3(w)] \vee [\exists x \; (\exists y \; (P_6(x,y) \Rightarrow P_4(w,x)))]) \wedge [\forall w \; (P_5(w))]$ Original sentence S:

Let's number all clauses:

 $(P_3(\mathbf{w}) \vee \neg P_1(\mathbf{w}) \vee \neg P_6(f(\mathbf{w}),\,g(\mathbf{w})) \vee P_4(\mathbf{w},\,f(\mathbf{w})))_1$

7. Convert to conjunction of disjuncts (CNF)

Create separate clause for each conjunct

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Example 2 Converting FOL to CNF: Example 2 Original sentence S: ∀x [∀y (Animal(y) ⇒ Loves(x, y))] ⇒ [∃y Loves(y, x)] By Implication Law (p ⇒ q ≡ ¬p ∨ q): ∀x ¬[∀y (Animal(y) ⇒ Loves(x, y))] ∨ [∃y Loves(y, x)] becomes: ∀x ¬[(∀y (¬Animal(y) ∨ Loves(x, y))] ∨ [∃y Loves(y, x)] ∃y Loves(y, x)] As ¬[[(∀y (¬Animal(y) ∨ Loves(x, y))] ∨ [∃y Loves(y, x)] ∃y [Innois Institute of Technology)	(ample 2
Converting FOL to CNF: Example 2 Original sentence S: ∀x [∀y (Animal(y) = Loves(x, y)] = [∃y Loves(y, x)] By Implication Law {p ⇒ q = ¬p ∨ q}: ∀x [∀y (Animal(y) ⇒ Loves(x, y)] > [∃y Loves(y, x)] becomes: ∀x ¬[∀y (Animal(y) ⇒ Loves(x, y)] ∨ [∃y Loves(y, x)] ∃\$ Illinois institute of Technology	Converting FOL to CNF: Example 2 Original sentence S: ∀x [∀y (Animal(y) = Loves(x, y)] = [∃y Loves(y, x)] By De Morgan's Law (¬(p ∨ q) = ¬p ∧ ¬q): ∀x [⟨∃y ¬(¬¬Animal(y) ∨ Loves(x, y)]] ∨ [∃y Loves(y, x)] becomes: ∀x [⟨∃y ¬(¬¬Animal(y) ∧ ¬(¬¬Loves(x, y))] ∨ [∃y Loves(y, x)] ∀x [⟨∃y ¬(¬¬¬Animal(y) ∧ ¬(¬Loves(x, y))] ∨ [∃y Loves(y, x)]
Converting FOL to CNF: Example 2 Original sentence S: Vx [Vy (Animal(v) = Loves(x, y)] = [3y Loves(y, x)] "Everyone who loves all animals is loved by someone" 1) 34 Illinois Institute of Technology	FOL to CNF: Example 2 (y) = Loves(x, y)] = [∃y Loves(y, x)] ¬∀x (p) = ∃x (¬p)): mal(y) × Loves(x, y)] ∨ [∃y Loves(y, x)] mal(x) × Loves(x, y)] ∨ [∃y Loves(y, x)]
Predicate (First-Order) Logic to CNF Variables and quantifiers are a challenge: 1. Eliminate all equivalences ⇔ and implications ⇒ 2. Reduce the scope of all ¬to single term (De Morgan) 3. Make all variable names unique (standardize apart) 4. Move quantifiers left (convert to prenex normal form) 5. Eliminate Existential quantifiers 6. Eliminate Universal quantifiers 7. Convert to conjunction of disjuncts 8. Create separate clause for each conjunct	rst-Order) Logic to CNF lers are a challenge: ralences ⇔ and implications ⇒ of all ¬to single term (De Morgan) names unique (standardize apart) left (convert to prenex normal form ial quantifiers (skolemization) al quantifiers

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8. Create separate clause for each conjunct

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