



CS3202: Logic, Specification and Verification

CS3202-LSV 2006–07

`cs3202.lec@cs.st-andrews.ac.uk`

Dr. James McKinna, RM 1.03

Dr. Stéphane Lengrand, Rm. 1.02

Lecture 6 (02/03/2007):
Predicate Logic —
Semantical notions, equality & conclusion

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables
 - particular functions from \mathcal{U}^n to \mathcal{U} interpreting function symbols
(with correct arity n)

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables
 - particular functions from \mathcal{U}^n to \mathcal{U} interpreting function symbols
(with correct arity n)
 - particular n -ary relations on \mathcal{U}
(= subsets of \mathcal{U}^n / functions from \mathcal{U}^n to booleans)
interpreting predicate symbols (with correct arity n)

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables
 - particular functions from \mathcal{U}^n to \mathcal{U} interpreting function symbols
(with correct arity n)
 - particular n -ary relations on \mathcal{U}
(= subsets of \mathcal{U}^n / functions from \mathcal{U}^n to booleans)
interpreting predicate symbols (with correct arity n)

A collection of such data is denoted \mathcal{M}

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables
 - particular functions from \mathcal{U}^n to \mathcal{U} interpreting function symbols
(with correct arity n)
 - particular n -ary relations on \mathcal{U}
(= subsets of \mathcal{U}^n / functions from \mathcal{U}^n to booleans)
interpreting predicate symbols (with correct arity n)

A collection of such data is denoted \mathcal{M}

We now define when it is considered a model of a wff.

Semantics of predicate logic

- We need
 - a *set of elements* \mathcal{U} to interpret terms
(i.e. the universe whose objects are what the syntax is meant to denote & speak about)
 - particular elements of \mathcal{U} interpreting constants & free variables
 - particular functions from \mathcal{U}^n to \mathcal{U} interpreting function symbols
(with correct arity n)
 - particular n -ary relations on \mathcal{U}
(= subsets of \mathcal{U}^n / functions from \mathcal{U}^n to booleans)
interpreting predicate symbols (with correct arity n)

A collection of such data is denoted \mathcal{M}

We now define when it is considered a model of a wff.

Models of predicate logic

- \mathcal{M} gives interpretation of constants and variables.

Extended to terms in the obvious way, using interpretation of functions given in \mathcal{M}

Models of predicate logic

- \mathcal{M} gives interpretation of constants and variables.
Extended to terms in the obvious way, using interpretation of functions given in \mathcal{M}
- an (applied) predicate $p(t_1, \dots, t_n)$ is interpreted as *true* if the interpretations of t_1, \dots, t_n are in the relation interpreting p
false if not.

Models of predicate logic

- \mathcal{M} gives interpretation of constants and variables.
Extended to terms in the obvious way, using interpretation of functions given in \mathcal{M}
- an (applied) predicate $p(t_1, \dots, t_n)$ is interpreted as *true* if the interpretations of t_1, \dots, t_n are in the relation interpreting p *false* if not.
- wff are interpreted as in propositional logic, using truth tables for propositional connectives $\wedge, \vee, \Rightarrow$
... + new case of quantifier

Models of predicate logic

- \mathcal{M} gives interpretation of constants and variables.
Extended to terms in the obvious way, using interpretation of functions given in \mathcal{M}
- an (applied) predicate $p(t_1, \dots, t_n)$ is interpreted as *true* if the interpretations of t_1, \dots, t_n are in the relation interpreting p *false* if not.
- wff are interpreted as in propositional logic, using truth tables for propositional connectives $\wedge, \vee, \Rightarrow$
... + new case of quantifier

Models of predicate logic

- $\forall x, A$ is interpreted as
true if *for all object c of the universe \mathcal{U}* , A is interpreted as `true` in the structure that extends \mathcal{M} by interpreting x as c
false if not.

Models of predicate logic

- $\forall x, A$ is interpreted as
true if *for all object c of the universe \mathcal{U}* , A is interpreted as `true` in the structure that extends \mathcal{M} by interpreting x as c
false if not.
- $\exists x, A$ is interpreted as
true if *there exists an object c of the universe \mathcal{U}* such that A is interpreted as `true` in the struct. that extends \mathcal{M} by interpreting x as c
false if not.

Models of predicate logic

- $\forall x, A$ is interpreted as
true if *for all object c of the universe \mathcal{U}* , A is interpreted as `true` in the structure that extends \mathcal{M} by interpreting x as c
false if not.
- $\exists x, A$ is interpreted as
true if *there exists an object c of the universe \mathcal{U}* such that A is interpreted as `true` in the struct. that extends \mathcal{M} by interpreting x as c
false if not.
- \mathcal{M} is a *model* of a formula A , written $\mathcal{M} \models A$, if the interpretation of A in \mathcal{M} is `true`.

Models of predicate logic

- $\forall x, A$ is interpreted as
true if *for all object c of the universe \mathcal{U}* , A is interpreted as `true` in the structure that extends \mathcal{M} by interpreting x as c
false if not.
- $\exists x, A$ is interpreted as
true if *there exists an object c of the universe \mathcal{U}* such that A is interpreted as `true` in the struct. that extends \mathcal{M} by interpreting x as c
false if not.
- \mathcal{M} is a *model* of a formula A , written $\mathcal{M} \models A$, if the interpretation of A in \mathcal{M} is `true`.
Again, notion of semantic entailment: $A_1, \dots, A_n \models A$

Models of predicate logic

- $\forall x, A$ is interpreted as
true if *for all object c of the universe \mathcal{U}* , A is interpreted as `true` in the structure that extends \mathcal{M} by interpreting x as c
false if not.
- $\exists x, A$ is interpreted as
true if *there exists an object c of the universe \mathcal{U}* such that A is interpreted as `true` in the struct. that extends \mathcal{M} by interpreting x as c
false if not.
- \mathcal{M} is a *model* of a formula A , written $\mathcal{M} \models A$, if the interpretation of A in \mathcal{M} is `true`.
Again, notion of semantic entailment: $A_1, \dots, A_n \models A$

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*.

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*.
Because of quantifiers, there is *no finite check* that the interpretation of a formula is *true* or *false*.

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*.
Because of quantifiers, there is *no finite check* that the interpretation of a formula is *true* or *false*.
In fact, this is *undecidable*.

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*.
Because of quantifiers, there is *no finite check* that the interpretation of a formula is *true* or *false*.

In fact, this is *undecidable*.

The syntactic notion of proof (e.g. Classical natural deduction) is sound & complete w.r.t. semantics

$$A_1, \dots, A_n \vdash A \text{ iff } A_1, \dots, A_n \models A$$

... hence, it cannot get round undecidability,

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*. Because of quantifiers, there is *no finite check* that the interpretation of a formula is *true* or *false*.

In fact, this is *undecidable*.

The syntactic notion of proof (e.g. Classical natural deduction) is sound & complete w.r.t. semantics

$$A_1, \dots, A_n \vdash A \text{ iff } A_1, \dots, A_n \models A$$

... hence, it cannot get round undecidability,

but proofs are finite objects that can capture infinite behaviour/properties.

Advantage on semantics.

Models of predicate logic

- The universe \mathcal{U} in \mathcal{M} can have *infinitely many elements*. Because of quantifiers, there is *no finite check* that the interpretation of a formula is *true* or *false*.

In fact, this is *undecidable*.

The syntactic notion of proof (e.g. Classical natural deduction) is sound & complete w.r.t. semantics

$$A_1, \dots, A_n \vdash A \text{ iff } A_1, \dots, A_n \models A$$

... hence, it cannot get round undecidability,

but proofs are finite objects that can capture infinite behaviour/properties.

Advantage on semantics.

The case of equality

- One particular binary predicate: $=$

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:
- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)

The case of equality

- One particular binary predicate: $=$

Usually comes with extra axioms / rules:

- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)

- Leibniz's axiom: $\frac{A\{x \mapsto t\} \quad t = u}{A\{x \mapsto u\}}$

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:
- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)
- Leibniz's axiom: $\frac{A\{x \mapsto t\} \quad t = u}{A\{x \mapsto u\}}$
- Example: Set Theory (Zermelo-Fraenkel)
No constants, no function symbols, 1 predicate symbol \in
(plus $=$ with the above two rules), and axioms.

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:
- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)
- Leibniz's axiom: $\frac{A\{x \mapsto t\} \quad t = u}{A\{x \mapsto u\}}$
- Example: Set Theory (Zermelo-Fraenkel)
No constants, no function symbols, 1 predicate symbol \in
(plus $=$ with the above two rules), and axioms.
- All Mathematics can be expressed in that framework

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:
- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)
- Leibniz's axiom: $\frac{A\{x \mapsto t\} \quad t = u}{A\{x \mapsto u\}}$
- Example: Set Theory (Zermelo-Fraenkel)
No constants, no function symbols, 1 predicate symbol \in
(plus $=$ with the above two rules), and axioms.
- All Mathematics can be expressed in that framework
COQ: an alternative?

The case of equality

- One particular binary predicate: $=$
Usually comes with extra axioms / rules:
- Reflexivity: $\frac{}{t = t}$ (no premiss: leaves $t = t$ are discharged)
- Leibniz's axiom: $\frac{A\{x \mapsto t\} \quad t = u}{A\{x \mapsto u\}}$
- Example: Set Theory (Zermelo-Fraenkel)
No constants, no function symbols, 1 predicate symbol \in
(plus $=$ with the above two rules), and axioms.
- All Mathematics can be expressed in that framework
COQ: an alternative?

Conclusion on predicate logic

- More powerful than propositional logic.

Conclusion on predicate logic

- More powerful than propositional logic.
- “Mathematics-complete” with axioms of Set Theory,
no wonder why it is undecidable

Conclusion on predicate logic

- More powerful than propositional logic.
- “Mathematics-complete” with axioms of Set Theory,
no wonder why it is undecidable

Numbers can be defined, and induction principles hold from these axioms,
but not convenient: Extending predicate logic is still useful for convenience.

Conclusion on predicate logic

- More powerful than propositional logic.
- “Mathematics-complete” with axioms of Set Theory,
no wonder why it is undecidable

Numbers can be defined, and induction principles hold from these axioms,
but not convenient: Extending predicate logic is still useful for convenience.

- Proof-terms to denote proof-trees?

Conclusion on predicate logic

- More powerful than propositional logic.
- “Mathematics-complete” with axioms of Set Theory,
no wonder why it is undecidable

Numbers can be defined, and induction principles hold from these axioms,
but not convenient: Extending predicate logic is still useful for convenience.

- Proof-terms to denote proof-trees?

Questions?