LECTURE 10: FIRST-ORDER LOGIC

Software Engineering
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1 Why not Propositional Logic?

- Consider the following statements:
  - *all monitors are ready*;
  - *X12 is a monitor*.
- We saw in an earlier lecture that these statements are *propositions*: their meaning is either *true* or *false*.
- Propositional logic is the most *abstract* level at which we can study logic.
- As we shall say, it is too *coarse grained* to allow us to represent and reason about the kind of statement we need to write in formal specification.

- Consider the following argument:

  all monitors are ready
  X12 is a monitor
  ____
  therefore X12 is ready

- Intuitively, we can see that this argument is *sound*: if we accept that the two *premises* (i.e., the statements above the line) are true, then we must accept that the *conclusion* is true also.

  (Later, we shall see how we can do this kind of reasoning formally.)
- The only way we could represent these statements in propositional logic would be:
  - let p be *all monitors ready*;
  - let q be . . .

  And the sense of the argument would be lost; in fact, if we represented the three statement in propositional logic, then we *could not* derive the conclusion.

2 First-Order Logic: Syntax

- We shall now introduce a generalisation of propositional logic called first-order logic (FOL). This new logic affords us much greater expressive power.
- First, we shall look at how the *language* of first-order logic is put together.

2.1 Terms

- The basic components of FOL are called *terms*.
- Essentially, a term is an object that *denotes* some object other than *true* or *false*.
- The simplest kind of term is a *constant*.
- A value such as 8 is a constant; the *denotation* of this term is the number 8 — a value that is contained in the sets $\mathbb{N}$ and $\mathbb{Z}$.
- We often use constants in maths; we introduce them by writing things like

  Let S be the set $\{1, 2, 3\}$.

  In this case, we have introduced a constant and made its denotation clear; we have given it an *interpretation*.
- We can have constants that stand for any kind of object; for example, we could have a constant that stood for (denoted) the individual 'Michael Wooldridge'.

- The second simplest kind of term is a *variable*.
- A variable can stand for anything in a set of objects.
- That is, a variable of type $\mathbb{N}$ could stand for any of the natural numbers.
- Lets just formalise this before going any further.
- **Definition:** A *constant* of type T is a name that denotes some particular object in the set T.
- **Definition:** A *variable* of type T is a name that can denote any value in the set T.

- We can now introduce a more complex class of terms — *functions*.
- The idea of functional terms in logic is similar to the idea of a function in programming: recall that in programming, a function is a procedure that takes some arguments, and *returns a value*.

  In Modula-2:

  ```
  PROCEDURE f(a1:T1; ... an:Tn) : T;
  ```

  this function takes n arguments; the first is of type `T1`, the second is of type `T2`, and so on. The function returns a value of type `T`.
- In FOL, we have a set of *function symbols*; each symbol corresponds to a particular function. (It denotes some function.)
- Each function symbol is associated with a natural number called its *arity*. This is just the number of arguments it takes.

- Each function symbol has a return-type associated with it...
- ... and each function symbol has an argument type associated with it.
- A *functional term* is then built up by *applying* a function symbol to the appropriate number of terms, of the appropriate type.
- Formally ...

  Definition: Let f be an arbitrary function symbol of type T, with arity $n \in \mathbb{N}$, taking arguments of type $T_1, \ldots, T_n$ respectively. Also, let $\tau_1, \ldots, \tau_n$ be terms of type $T_1, \ldots, T_n$ respectively. Then

  $$f(\tau_1, \ldots, \tau_n)$$

  is a functional term.

- All this sounds complicated, but isn't. Consider a function *plus*, which takes just two arguments, each of which is a natural number, and returns the first number added to the second.

  Then:
  - $plus(2, 3)$ is an acceptable functional term;
  - $plus(0, 1)$ is acceptable;
  - $plus(plus(1, 2), 4)$ is acceptable;
  - $plus(plus(plus(0, 1), 2), 4)$ is acceptable;

  but
  - $plus(-1, 0)$ isn't;
  - and neither is $plus(0.1, 2)$.

- In maths, we have many functions; the obvious ones are

  $$+ \quad - \quad / \quad * \quad \sqrt{\quad} \quad \sin \quad \cos \quad \ldots$$

- The fact that we write

  $$2 + 3$$

  instead of something like

  $$plus(2, 3)$$

  is merely a matter of convention, and is not relevant from the point of view of logic; all these are functions in exactly the way we have defined.

- Using functions, constants, and variables, we can build up *expressions*, e.g.:

  $$(x + 3) * \sin 90$$

  (which might just as well be written

  $$times(plus(x, 3), sin(90))$$

  for all it matters.)

2.2 Predicates

- In addition to having terms, FOL has *relational operators*, which capture relationships between objects.
- The language of FOL contains a stock of *predicate symbols*.
- These symbols stand for *relationships between objects*.
- Again, each predicate symbol has an associated *arity*...
- ... and each argument has a type.
- **Definition:** Let P be a predicate symbol of arity $n \in \mathbb{N}$, which takes arguments of types $T_1, \ldots, T_n$. Then if $\tau_1, \ldots, \tau_n$ are terms of type $T_1, \ldots, T_n$ respectively, then

  $$P(\tau_1, \ldots, \tau_n)$$

  is a predicate, which will either be *true* or *false* under some interpretation.

- EXAMPLE. Let *gt* be a predicate symbol with the intended interpretation 'greater than'. It takes two arguments, each of which is a natural number.

  Then:
  - $gt(4, 3)$ is a predicate, which evaluates to *true*;
  - $gt(3, 4)$ is a predicate, which evaluates to *false*.

  but
  - $gt(-1, 2)$ isn't a predicate.

- The following are standard mathematical predicate symbols:

  $$> \; < \; = \; \geq \; \leq \; \neq \; \in \; \subset \; \subseteq \; \ldots$$

- Once again, the fact that we are normally write $x > y$ instead of $gt(x, y)$ is just convention.
- We can build up more complex predicates using the connectives of propositional logic:

  $$(2 > 3) \wedge (6 = 7) \vee (\sqrt{4} = 2)$$

- So a predicate just expresses a relationship between some values.
- What happens if a predicate contains *variables*: can we tell if it is true or false?

  Not usually; we need to know an *interpretation* for the variables.
- A predicate that contains no variables is a proposition.
- Predicates of arity 1 are called *properties*.
- EXAMPLE. The follolwing are properties:

  $$Man(x)$$
  $$Mortal(x)$$
  $$Malfunctioning(x).$$
- Predicate that have arity 0 (i.e., take no arguments) are called *primitive propositions*.

3 Quantifiers

- We now come to the central part of first order logic: *quantification*.
- Consider trying to represent the following statements:
  - *all men have a mother*;
  - *every natural number has a prime factor*.
- We can't represent these using the apparatus we've got so far; we need *quantifiers*.

- In Z, we shall use three quantifers:

  $\forall$ — *the universal quantifier*;
  is read 'for all...'

  $\exists$ — *the existential quantifier*;
  is read 'there exists...'

  $\exists_1$ — *the unique quantifier*;
  is read 'there exists a unique...'

- The simplest form of quantified formula in Z is as follows:

  $$quantifier\ signature \bullet predicate$$

  where
  - *quantifier* is one of $\forall$, $\exists$, $\exists_1$;
  - *signature* is of the form

    $$variable : type$$
  - and *predicate* is a predicate.

- EXAMPLES.
  - $\forall x : Man \bullet Mortal(x)$
    'For all x of type *Man*, x is mortal.'
    (i.e. all men are mortal)
  - $\forall x : Man \bullet \exists_1 y : Woman \bullet MotherOf(x, y)$
    'For all x of type *Man*, there exists a unique y of type *Woman*, such that y is the mother of x.'
  - $\exists m : Monitor \bullet MonitorState(m, ready)$
    'There exists a monitor that is in a ready state.'
  - $\forall r : Reactor \bullet \exists_1 t : 100 \mathinner{..} 1000 \bullet Temp(r) = t$
    'Every reactor will have a temperature in the range 100 to 1000.'

- More examples:
  - $\exists n : \mathbb{N} \bullet n = (n * n)$
    'Some natural number is equal to its own square.'
  - $\exists c : EC \bullet Borders(c, Albania)$
    'Some EC country borders Albania.'
  - $\forall m, n : Person \bullet \neg Superior(m, n)$
    'No person is superior to another.'
  - $\forall m : Person \bullet \neg \exists n : Person \bullet Superior(m, n)$
    Ditto.

4 Comments

- Note that universal quantification is similar to conjunction:

  $$\forall n : \{2, 4, 6\} \bullet Even(n)$$

  is the same as

  $$Even(2) \wedge Even(4) \wedge Even(6).$$

- In the same way, existential quantification is the same as disjunction:

  $$\exists n : \{7, 8, 9\} \bullet Prime(n)$$

  is the same as

  $$Prime(7) \vee Prime(8) \vee Prime(9).$$

- The universal and existential quantifiers are in fact *duals* of each other:

  $$\forall x : T \bullet P(x) \;\Leftrightarrow\; \neg \exists x : T \bullet \neg P(x)$$

  Saying that everything has some property is the same as saying that there is nothing that does not have the property.

  $$\exists x : T \bullet P(x) \;\Leftrightarrow\; \neg \forall x : T \bullet \neg P(x)$$

  Saying that there is something that has the property is the same as saying that its not the case that everything doesn't have the property.

5 Decidability

- In propositional logic, we saw that some formulae were tautologies — they had the property of being true under all interpretations.
- We also saw that there was a procedure which could be used to tell whether any formula was a tautology — this procedure was the truth-table method.
- A formula of FOL that is true under all interpretations is said to be *valid*.
- Now we can't use truth tables to tell us whether a formula of FOL is valid.
- Is there any other procedure that we can use, that will be guaranteed to tell us, in a finite amount of time, whether a FOL formula is, or is not, valid?
- The answer is *no*.
- FOL is for this reason said to be *undecidable*.