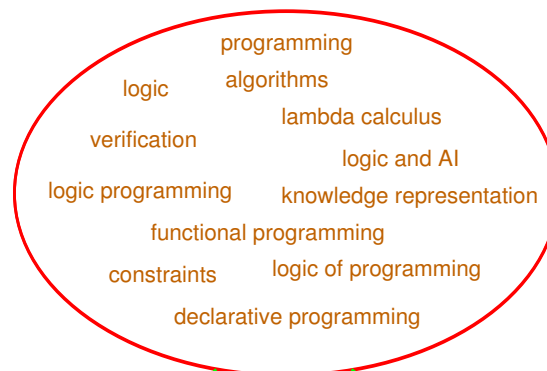


A Motivational Introduction to Computational Logic and (Constraint) Logic Programming

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Computational Logic



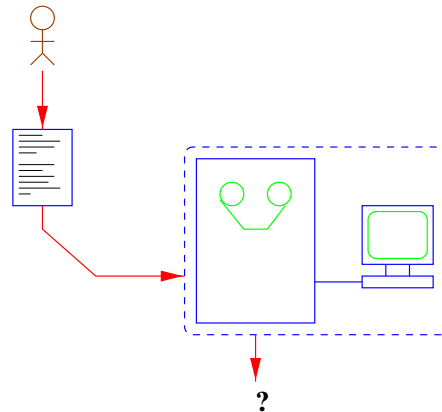
Logic of Computation

program verification
proving properties

Declarative Programming

direct use of logic
as a programming tool

The Program Correctness Problem



- Conventional models of using computers – not easy to determine correctness!
 - ◇ Has become a very important issue, not just in safety-critical apps.
 - ◇ Components with assured quality, being able to give a warranty, ...
 - ◇ Being able to run untrusted code, certificate carrying code, ...

2

A Simple Imperative Program

- Example:

```
#include <stdio.h>
main() {
    int Number, Square;
    Number = 0;
    while(Number <= 5)
        { Square = Number * Number;
          printf("%d\n",Square);
          Number = Number + 1; } }
```

- Is it correct? With respect to what?
 - A suitable formalism:
 - ◇ to provide *specifications* (describe problems), and
 - ◇ to reason about the *correctness of programs* (their *implementation*).
- is needed.

3

Natural Language

“Compute the squares of the natural numbers which are less or equal than 5.”

Ideal at first sight, but:

- ◇ verbose
- ◇ vague
- ◇ ambiguous
- ◇ needs context (assumed information)
- ◇ ...

Philosophers and Mathematicians already pointed this out a long time ago...

Logic

- A means of clarifying / formalizing the human thought process

- Logic for example tells us that (classical logic)

Aristotle likes cookies, and

Plato is a friend of anyone who likes cookies

imply that

Plato is a friend of Aristotle

- Symbolic logic:

A shorthand for classical logic – plus many useful results:

$a_1 : \text{likes}(\text{aristotle}, \text{cookies})$

$a_2 : \forall X \text{ likes}(X, \text{cookies}) \rightarrow \text{friend}(\text{plato}, X)$

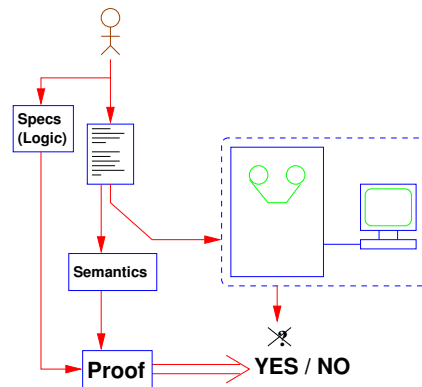
$t_1 : \text{friend}(\text{plato}, \text{aristotle})$

$T[a_1, a_2] \vdash t_1$

- But, can logic be used:

- ◇ To represent the problem (specifications)?
- ◇ Even perhaps to solve the problem?

Using Logic



- For expressing specifications and reasoning about the correctness of programs we need:
 - ◊ Specification languages (assertions), modeling, ...
 - ◊ Program semantics (models, axiomatic, fixpoint, ...).
 - ◊ Proofs: program *verification* (and debugging, equivalence, ...).

6

Generating Squares: A Specification (I)

Numbers —we will use “Peano” representation for simplicity:

$0 \rightarrow 0$ $1 \rightarrow s(0)$ $2 \rightarrow s(s(0))$ $3 \rightarrow s(s(s(0)))$...

- Defining the natural numbers:
 $nat(0) \wedge nat(s(0)) \wedge nat(s(s(0))) \wedge \dots$
- A better solution:
 $nat(0) \wedge \forall X (nat(X) \rightarrow nat(s(X)))$
- Order on the naturals:
 $\forall X (le(0, X)) \wedge$
 $\forall X \forall Y (le(X, Y) \rightarrow le(s(X), s(Y)))$
- Addition of naturals:
 $\forall X (nat(X) \rightarrow add(0, X, X)) \wedge$
 $\forall X \forall Y \forall Z (add(X, Y, Z) \rightarrow add(s(X), Y, s(Z)))$

7

Generating Squares: A Specification (II)

- Multiplication of naturals:
 $\forall X (nat(X) \rightarrow mult(0, X, 0)) \wedge$
 $\forall X \forall Y \forall Z \forall W (mult(X, Y, W) \wedge add(W, Y, Z) \rightarrow mult(s(X), Y, Z))$
- Squares of the naturals:
 $\forall X \forall Y (nat(X) \wedge nat(Y) \wedge mult(X, X, Y) \rightarrow nat_square(X, Y))$

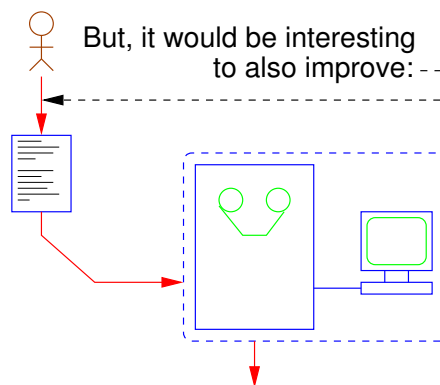
We can now write a *specification* of the (imperative) program, i.e., conditions that we want the program to meet:

- *Precondition*:
empty.
- *Postcondition*:
 $\forall X (output(X) \leftarrow (\exists Y nat(Y) \wedge le(Y, s(s(s(s(0)))))) \wedge nat_square(Y, X))$

8

Alternative Use of Logic?

- So, logic allows us to *represent problems* (program specifications).



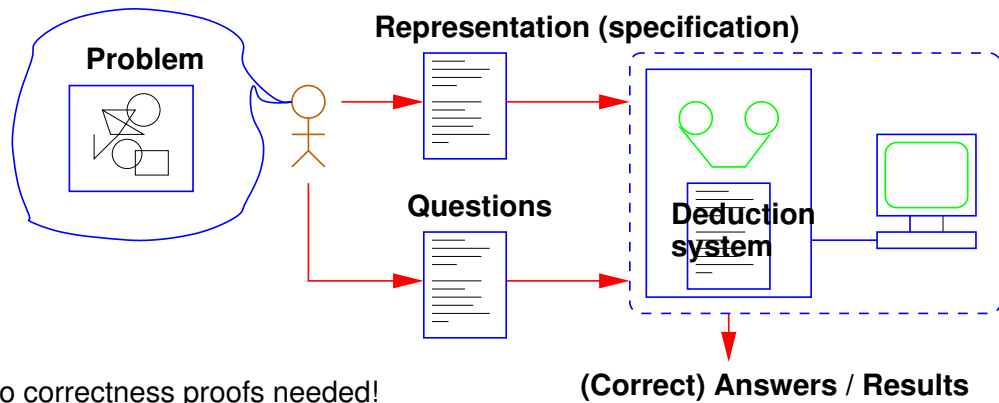
i.e., the process of implementing solutions to problems.

- The importance of Programming Languages (and tools).
- Interesting question: can logic help here too?

9

From Representation/Specification to Computation

- Assuming the existence of a *mechanical proof method* (deduction procedure) a new view of problem solving and computing is possible [Greene]:
 - ◇ program once and for all the deduction procedure in the computer,
 - ◇ find a suitable *representation* for the problem (i.e., the *specification*),
 - ◇ then, to obtain solutions, ask questions and let deduction procedure do rest:



- No correctness proofs needed!

10

Computing With Our Previous Description / Specification

Query	Answer
$nat(s(0)) ?$	(yes)
$\exists X add(s(0), s(s(0)), X) ?$	$X = s(s(s(0)))$
$\exists X add(s(0), X, s(s(s(0)))) ?$	$X = s(s(0))$
$\exists X nat(X) ?$	$X = 0 \vee X = s(0) \vee X = s(s(0)) \vee \dots$
$\exists X \exists Y add(X, Y, s(0)) ?$	$(X = 0 \wedge Y = s(0)) \vee (X = s(0) \wedge Y = 0)$
$\exists X nat_square(s(s(0)), X) ?$	$X = s(s(s(s(0))))$
$\exists X nat_square(X, s(s(s(s(0)))) ?$	$X = s(s(0))$
$\exists X \exists Y nat_square(X, Y) ?$	$(X = 0 \wedge Y = 0) \vee (X = s(0) \wedge Y = s(0)) \vee (X = s(s(0)) \wedge Y = s(s(s(0)))) \vee \dots$
$\exists X output(X) ?$	$X = 0 \vee X = s(0) \vee X = s(s(s(s(0)))) \vee X = s^9(0) \vee X = s^{16}(0) \vee X = s^{25}(0)$

11

Which Logic?

- We have already argued the convenience of representing the problem in logic, but
 - ◇ which logic?
 - * propositional
 - * predicate calculus (first order)
 - * higher-order logics
 - * modal logics
 - * λ -calculus, ...
 - ◇ which reasoning procedure?
 - * natural deduction, classical methods
 - * resolution
 - * Prawitz/Bibel, tableaux
 - * bottom-up fixpoint
 - * rewriting
 - * narrowing, ...

12

Issues

- We try to maximize expressive power.
- But one of the main issues is whether we have an **effective** reasoning procedure.
- It is important to understand the underlying properties and the theoretical limits!
- Example: propositions vs. first-order formulas.

- ◇ Propositional logic:

“spot is a dog” p
“dogs have tail” q

but how can we conclude that Spot has a tail?

- ◇ Predicate logic extends the expressive power of propositional logic:

$dog(spot)$
 $\forall X dog(X) \rightarrow has_tail(X)$

now, using deduction we can conclude:

$has_tail(spot)$

13

Comparison of Logics (I)

- Propositional logic:

“spot is a dog” p
+ decidability/completeness
- limited expressive power
+ practical deduction mechanism

→ circuit design, “answer set” programming, ...

- Predicate logic: (first order)

“spot is a dog” $dog(spot)$
+/- decidability/completeness
+/- good expressive power
+ practical deduction mechanism (e.g., **SLD-resolution**)

→ classical logic programming!

14

Comparison of Logics (II)

- Higher-order predicate logic:

“There is a relationship for spot” $X(spot)$
- decidability/completeness
+ good expressive power
– practical deduction mechanism

But interesting subsets → HO logic programming, functional-logic prog., ...

- Other logics: decidability? Expressive power? Practical deduction mechanism?

Often (very useful) variants of previous ones:

- ◇ Predicate logic + constraints (in place of unification)
→ constraint programming!
- ◇ Propositional temporal logic, etc.

- Interesting case: λ -calculus

+ similar to predicate logic in results, allows higher order
- does not support predicates (relations), only functions

→ functional programming!

15

Generating squares by SLD-Resolution – Logic Programming (I)

- We code the problem as definite (Horn) clauses:
 $nat(0)$
 $\neg nat(X) \vee nat(s(X))$
 $\neg nat(X) \vee add(0, X, X)$
 $\neg add(X, Y, Z) \vee add(s(X), Y, s(Z))$
 $\neg nat(X) \vee mult(0, X, 0)$
 $\neg mult(X, Y, W) \vee \neg add(W, Y, Z) \vee mult(s(X), Y, Z)$
 $\neg nat(X) \vee \neg nat(Y) \vee \neg mult(X, X, Y) \vee nat_square(X, Y)$
- **Query:** $nat(s(0))$?
- In order to refute: $\neg nat(s(0))$
- **Resolution:**
 $\neg nat(s(0))$ with $\neg nat(X) \vee nat(s(X))$ gives $\neg nat(0)$
 $\neg nat(0)$ with $nat(0)$ gives \square
- **Answer:** (*yes*)

16

Generating squares by SLD-Resolution – Logic Programming (II)

- $nat(0)$
 $\neg nat(X) \vee nat(s(X))$
 $\neg nat(X) \vee add(0, X, X)$
 $\neg add(X, Y, Z) \vee add(s(X), Y, s(Z))$
 $\neg nat(X) \vee mult(0, X, 0)$
 $\neg mult(X, Y, W) \vee \neg add(W, Y, Z) \vee mult(s(X), Y, Z)$
 $\neg nat(X) \vee \neg nat(Y) \vee \neg mult(X, X, Y) \vee nat_square(X, Y)$
- **Query:** $\exists X \exists Y add(X, Y, s(0))$?
- In order to refute: $\neg add(X, Y, s(0))$
- **Resolution:**
 $\neg add(X, Y, s(0))$ with $\neg nat(X) \vee add(0, X, X)$ gives $\neg nat(s(0))$
 $\neg nat(s(0))$ solved as before
- **Answer:** $X = 0, Y = s(0)$
- **Alternative:**
 $\neg add(X, Y, s(0))$ with $\neg add(X, Y, Z) \vee add(s(X), Y, s(Z))$ gives $\neg add(X, Y, 0)$

17

Generating Squares in a Practical Logic Programming System (I)

```
:- module(_,_,['bf/af']).

nat(0) <- .
nat(s(X)) <- nat(X).

le(0,_X) <- .
le(s(X),s(Y)) <- le(X,Y).

add(0,Y,Y) <- nat(Y).
add(s(X),Y,s(Z)) <- add(X,Y,Z).

mult(0,Y,0) <- nat(Y).
mult(s(X),Y,Z) <- add(W,Y,Z), mult(X,Y,W).

nat_square(X,Y) <- nat(X), nat(Y), mult(X,X,Y).

output(X) <- nat(Y), le(Y,s(s(s(s(s(0)))))), nat_square(Y,X).
```

18

Generating Squares in a Practical Logic Programming System (II)

Query	Answer
?- nat(s(0)).	yes
?- add(s(0),s(s(0)),X).	X = s(s(s(0)))
?- add(s(0),X,s(s(s(0)))).	X = s(s(0))
?- nat(X).	X = 0 ; X = s(0) ; X = s(s(0)) ; ...
?- add(X,Y,s(0)).	(X = 0 , Y=s(0)) ; (X = s(0) , Y = 0)
?- nat_square(s(s(0)), X).	X = s(s(s(s(0))))
?- nat_square(X,s(s(s(s(0))))).	X = s(s(0))
?- nat_square(X,Y).	(X = 0 , Y=0) ; (X = s(0) , Y=s(0)) ; (X = s(s(0)) , Y=s(s(s(s(0)))))) ; ...
?- output(X).	X = 0 ; X = s(0) ; X = s(s(s(s(0)))) ; ...

19

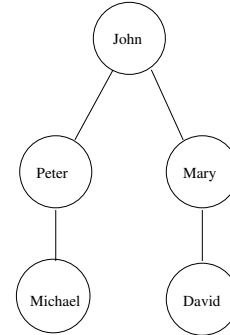
Introductory example (I) – Family relations

```
father_of(john, peter)
father_of(john, mary)
father_of(peter, michael)
mother_of(mary, david)
 $\forall X \forall Y (\exists Z (father\_of(X, Z) \wedge father\_of(Z, Y)) \rightarrow grandfather\_of(X, Y))$ 
 $\forall X \forall Y (\exists Z (father\_of(X, Z) \wedge mother\_of(Z, Y)) \rightarrow grandfather\_of(X, Y))$ 
```

```
father_of(john, peter).
father_of(john, mary).
father_of(peter, michael).
mother_of(mary, david).
```

```
grandfather_of(L,M) :- father_of(L,K),
                        father_of(K,M).
```

```
grandfather_of(X,Y) :- father_of(X,Z),
                        mother_of(Z,Y).
```



- How can grandmother_of/2 be represented?
- What does grandfather_of(X,david) mean? And grandfather_of(john,X)?

20

Introductory example (II) - Testing membership in lists

- Declarative view:

- ◊ Suppose there is a functor $f/2$ such that $f(H, T)$ represents a list with head H and tail T .

- ◊ Membership definition: $X \in L \leftrightarrow \begin{cases} X \text{ is the head of } L \\ \text{or } X \text{ is member of the tail of } L \end{cases}$

- ◊ Using logic:

```
 $\forall X \forall L (\exists T (L = f(X, T) \rightarrow member(X, L)))$ 
```

```
 $\forall X \forall L (\exists Z \exists T (L = f(Z, T) \wedge member(X, T) \rightarrow member(X, L)))$ 
```

- ◊ Using Prolog:

```
member(X, f(X, T)).
member(X, f(Z, T)) :- member(X, T).
```

- Procedural view (but for checking membership only!):

- ◊ Traverse the list comparing each element until X is found or list is finished

```
/* Testing array membership in C */
int member(int x, int list[LISTSIZE]) {
    for (int i = 0; i < LISTSIZE; i++)
        if (x == list[i]) return TRUE;
    return FALSE;
}
```

21

A (very brief) History of Logic Programming (I)

- **60's**

- ◇ Greene: problem solving.
- ◇ Robinson: linear resolution.

- **70's**

- ◇ **(early)** Kowalski: procedural interpretation of Horn clause logic. Read:
 A if B_1 and B_2 and \dots and B_n as:
to solve (execute) A , solve (execute) B_1 and B_2 and, ..., B_n
- ◇ **(early)** Colmerauer: specialized theorem prover (Fortran) embedding the procedural interpretation: Prolog (Programmation et Logique).
- ◇ In the U.S.: "next-generation AI languages" of the time (i.e. planner) seen as inefficient and difficult to control.
- ◇ **(late)** D.H.D. Warren develops DEC-10 Prolog compiler, almost completely written in Prolog. Very efficient (same as LISP). Very useful control builtins.

A (very brief) History of Logic Programming (II)

- **Late 80's, 90's**

- ◇ Major research in the basic paradigms and advanced implementation techniques: Japan (Fifth Generation Project), US (MCC), Europe (ECRC, ESPRIT projects).
- ◇ Numerous commercial Prolog implementations, programming books, and a *de facto* standard, the Edinburgh Prolog family.
- ◇ First parallel and concurrent logic programming systems.
- ◇ CLP – Constraint Logic Programming: Major extension – many new applications areas.
- ◇ 1995: ISO Prolog standard.

Currently

- Many commercial CLP systems with fielded applications.
- Extensions to full higher order, inclusion of functional programming, ...
- Highly optimizing compilers, automatic parallelism, automatic debugging.
- Concurrent constraint programming systems.
- Distributed systems.
- Object oriented dialects.
- Applications
 - ◇ Natural language processing
 - ◇ Scheduling/Optimization problems
 - ◇ AI related problems
 - ◇ (Multi) agent systems programming.
 - ◇ Program analyzers
 - ◇ ...