Computational Logic:
(Constraint) Logic Programming

Theory, practice, and implementation

The *Ciao* Logic Programming Environment – A Tutorial –

The following people have contributed to this course material:

Manuel Hermenegildo (editor), Francisco Bueno, Manuel Carro, Germán Puebla, Pedro López, and Daniel Cabeza, Technical University of Madrid, Spain

Introduction: The Ciao Program Development System

- Ciao is a next-generation (C)LP programming environment – features:
  - ◇ Free software (GNU license).
  - ◇ Designed to be *extensible* and *analyzable*.
  - ◇ Pure kernel (*no "built-ins"*); subsumes ISO-Prolog (transparently) via *library*.
  - ◇ Support for *programming in the large*:
    - * robust module/object system, separate/incremental compilation, ...
    - * "industry standard" performance.
    - * (semi-automatic) interfaces to other languages, databases, etc.
    - * assertion language, automatic static inference and checking, autodoc, ...
  - ◇ Support for programming *in the small*:
    - * scripts, small (static/dynamic/lazy-load) executables, ...
  - ◇ Support for several paradigms:
    - * functions, higher-order, objects, constraint domains, ...
    - * concurrency, parallelism, distributed execution, ...
  - ◇ Advanced Emacs environment (with e.g., automatic access to documentation).

Introduction: The Ciao Program Development System (Contd.)

- Components of the environment (independent, written in Ciao Prolog):

`ciaosh`:	Standard top-level shell.
`ciaoc`:	Standalone compiler.
`ciao-shell`:	Script interpreter.
`lpdoc`:	Documentation generator (info, ps, pdf, html, ...).
`ciaopp`:	Preprocessor (assertion checker/optimizer/parallelizer...).

  + Many libraries:

  - Records (argument names).
  - Persistent predicates
    (automatically updated and stored in permanent media).
  - Transparent interface to databases.
  - Interfaces to C, Java, tcl-tk, etc.
  - Distributed execution.
  - Interface to current Internet standards and protocols (e.g., the PiLLoW library: HTML, forms, http protocol, VRML generation etc.), ...

The Ciao Module System

- Ciao implements a module system [6] which meets a number of objectives:
  - ◇ High extensibility in syntax and functionality.
  - ◇ Amenability to modular (separate) processing of program components.
  - ◇ Amenability to (modular) global analysis.
  - ◇ Greatly enhanced error detection (e.g., undefined predicates).
  - ◇ Support for meta-programming and higher-order.
  - ◇ Compatibility with official and de-facto standards.
  - ◇ Backward compatible with files which are not modules.

The Ciao Module System (Contd.)

- Some more specific characteristics [6]:
  - ◇ Syntax, flags, expansions, etc. are local to modules.
  - ◇ Compile-time and run-time code is clearly separated (e.g., expansion code is compile-time and does not go into executables).
  - ◇ "Built-ins" are in libraries and can be loaded into and/or unloaded from the context of a given module.
  - ◇ Dynamic parts are more isolated.
  - ◇ Directives are not queries.
  - ◇ Richer treatment of meta-predicates and higher-order.
  - ◇ The entry points to modules are statically defined.
  - ◇ Module qualification used only for disambiguating predicate names.
  - ◇ All module text must be available or in related parts.
- A resulting notion: **packages** (see later).

Modular Compilation/Processing

- The Ciao compiler [7]:
  - ◇ Uses a generic program processing framework (library).
  - ◇ Can compile separately program components.
  - ◇ Builds small, standalone executables.
  - ◇ With different linking regimes.
- The actual compiler is a component used by:
  - ◇ The stand-alone compiler (`ciaoc`).
  - ◇ The top-level shell (`ciaosh`).
  - ◇ Any user executable that may need to compile programs.
- It is based on a generic program-processing *library* which:
  - ◇ Understands the module system.
  - ◇ Abstracts away many functionalities common to several modular program processing tasks.

The Generic Code-Processing Framework

- Many program processing tools (compiler, preprocessor, documenter, ...) require:
  - ◇ Reading programs into a normalized internal representation.
  - ◇ Dealing with syntactic extensions in the process.
  - ◇ “Understanding” the module system (imports, exports, multifiles, scope, etc.).
- We have abstracted this functionality into a library which offers:
  - ◇ A normalized internal representation with line numbers, etc.
  - ◇ Modular, incremental, separate, and global processing of files.
  - ◇ Dependency checking (what needs to be recompiled).
  - ◇ Automatic creation/update of interface/dependency (`.itf`) files.
  - ◇ Static detection of syntax and generic module-related errors.
  - ◇ Parameterizable via higher order.
- Used by the low-level (WAM) compiler, the preprocessor (global analyzers, etc), the automatic documentation generator, and the assertion preprocessor.
- Ensures consistency among the various code-processing tools.

Linking Regimes of Executables

- The compiler produces executables by collecting the bytecode (`.po`) files of the program components, and linking them in a file to be loaded by the Ciao engine.
- Modules can be linked in the executable in three ways:
  - ◇ Statically: bytecode of the module added to the executable.
    + When running the program, the module does not have to be available.
    − Larger executables and more compilation time.
  - ◇ Dynamically: bytecode loaded at startup from standard locations.
    + Smaller executable, flexibility (libraries can be updated without recompiling executables).
    − Module has to be accessible at run-time.
  - ◇ Lazily: bytecode loaded when a predicate of the module is called.
    + Useful when not all capabilities of an application are used in every run.
    − Not possible for every module. The compiler has to produce stump code.
- Executables may be compressed: smaller but (sometimes) slower startup.
- Stand-alone architecture-dependent executables may also be created.

The Ciao-Emacs Development Environment

- Customized program editor:
  In one (simple and powerful) word: Emacs!!
- A Ciao mode (`ciao.el`) including:
  - ◇ Incremental syntax highlighting of source code.
  - ◇ Direct access to on-line documentation (help on what the cursor is on).
  - ◇ Menu-guided support for compilation, top-level, preprocessing, ...
  - ◇ Also to *generation* of documentation.
  - ◇ Location of errors from compiler (and preprocessor) on source code.
  - ◇ Support for source code debugging.
  - ◇ Plus many other features!

Ciao Mode Menu

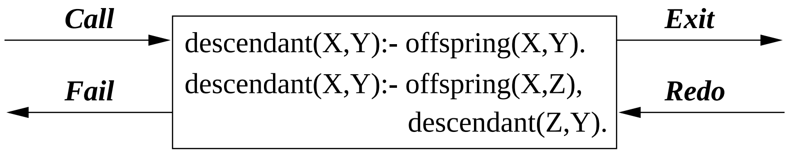
HELP	
Help (for symbol under cursor)	(C-c TAB)
Complete symbol under cursor	(C-c /)
Ciao system manual	
List all key bindings	
TOP-LEVEL/COMPILER	
Start ciao top level	(C-c t)
(Re)Load buffer into top level	(C-c l)
(Re)Load all modules as necessary	(C-c L)
Locate (next) preproc/compiler error msg	(C-c ‘)
Remove preproc/compiler error mark	(C-c e)
Query and main file	
Check buffer syntax (incl. assertions)	(C-c E)
Make executable from buffer	(C-c x)
Make object file (.po) from buffer	(C-c o)
Make active module from buffer	(C-c a)
Insert script header	(C-c I S)

Ciao Mode Menu (Contd.)

TOP-LEVEL/DEBUGGER	
(Un)Debug buffer source	(C-c d)
Select debug mode	(C-c m)
Select multiple buffers for debug	(C-c M-m)
Breakpoints	
Toggle debug mode (jump to bkp or spypt)	(C-c S d)
Toggle trace mode	(C-c S t)
(Re)Load region (for debug)	(C-c r)
(Re)Load predicate (for debug)	(C-c p)
SET MODE DEFAULTS)	
TRADITIONAL PROLOG COMMANDS (also for SICStus)	
Ciao/Prolog mode version	(C-c v)

Debugging in Ciao

- The traditional interface to the “byrd–box” debugger is available:



Call

Fail

descendant(X,Y):- offspring(X,Y).
descendant(X,Y):- offspring(X,Z),
descendant(Z,Y).

Exit

Redo

```
+  13  7  Call: T user:descendant(dani,_123) ?
```

- In addition, source-level tracking of the debugging process is supported:
  - ◇ Simultaneous visualization of tracing messages and byrd-box ports in the source code.
  - ◇ Placing break-points directly on the source code.
- Debugging modes can be toggled on a per-module basis:
  `debug_module/1`, `nodebug_module/1`, `debug_module_source/1`
- Easiest: use the Emacs environment.
- The debugger is also a library →
  Debugging also available in standalone executables! (see later).

Breakpoints

- Breakpoints are associated to literals rather than to predicates (as spypoints are).
- Spypoints trace every goal of the predicate, breakpoints only those arising from the selected literal in the program source.
- Information associated with a breakpoint:
  - ◇ File name.
  - ◇ Predicate name.
  - ◇ Start and end lines of the clause.
  - ◇ Number of literal in the clause & actual line of the literal.
- Set/unset/list breakpoints:
  - ◇ `breakpt/6`
  - ◇ `nobreakpt/6`
  - ◇ `nobreakall/0`
  - ◇ `list_breakpt/0`
- Easiest to use from the Emacs environment.

Using the Debugger

- Activate debugging mode (for the module) and load the code (from the file).
- Toggle debugging modes.
- Set/unset/list breakpoints.
- Plus the classical spy-points.

Everything transparent to the user within Emacs!

- Plus the usual menu commands of the tracer.
- Additionally:
  - ◇ Source-debugging also useful outside Emacs:

```
          In /home/clip/ciao/dbgex.pl (5-9) descendant-1
+   13  7  Call: T user:descendant(dani,_123) ?
```

  - ◇ Debugger works also in (stand-alone) compiled executables:

```
:- use_package(debug).
```

Packages

- Libraries defining extensions to the language.
- Made possible thanks to:
  - ◇ Local nature of syntax extensions.
  - ◇ Clear distinction between compile-time and run-time code.
- Typically consist of:
  - ◇ A main source file to be *included* as part of the file using the library, with declarations (`op`, `new_declaration`, etc . . .).
  - ◇ Code needed at compile time to make translations (loaded by a `load_compilation_module` directive).
  - ◇ Code to be used at run-time (loaded using `use_module` directives).
- Examples: `dcg` (definite clause grammars), `argnames` (accessing term/predicate arguments by name), `iso` (ISO-Prolog compatibility package), `functions` (functional syntax), `class` (object oriented extension), `persdb` (persistent database), `assertions` (to include program assertions – see [22]), . . .

Package Example: Functional Notation (functions)

- Functional notation: defined via (local) ops/expansions.
  Provides simple syntactic translation to predicate definitions/calls:
  - ◇ Defining function `F/N` implies defining predicate `F/(N+1)`.
  - ◇ Any predicate `P/(N+1)` can be used as a function `P/N`.
  - ◇ The last argument of the predicate holds the result of the function.
- Using functions does not incur in run-time slowdowns.
- Function applications are recognized by:
  - ◇ Marking them with the prefix operator ~
  - ◇ A `:- function(F/N)` declaration makes all occurrences of a `F/N` functor to be regarded as a function call.
  - ◇ Arithmetic operators are translated to `is/2` calls (optional).
- Example: defining `fact/1` factorial function (and `fact/2` predicate!)

```
:- use_package(functions).
fact(0) := 1.
fact(N) := N * ~fact(--N) :- N > 0.
```

Functions Package: Examples – Array Access

- Assume multi-dimensional arrays such as:

```
:- use_package(functions).

array([N],A) :-
        functor(A,a,N).
array([N|Ms],A) :-
        functor(A,a,N),
        rows(N,Ms,A).

rows(0,_Ms,_A).
rows(N,Ms,A) :-
        N>0,
        arg(N,A,Arg),
        array(Ms,Arg),
        rows(N-1,Ms,A).
```

Functions Package: Examples – Array Access

- We can now define the array access function with some syntactic sugar:

```
:- op(45, xfx, [@]).
:- function '@'/2 .

@(V,[I])    := ~arg(I,V).
@(V,[I|Js]) := @(~arg(I,V),Js).
```

- And use it: `?- array([2,2],M), M@[2,1] = 3, display(M).`
- E.g., in a vector addition:

```
vecplus(V1,V2,V3) :-
        array([N],V1), array([N],V2), array([N],V3), vecplus_(N,V1,V2,V3).

vecplus_(0,_,_,_).
vecplus_(N,V1,V2,V3) :-  N>0,
                         V3@[N] = V1@[N] + V2@[N],
                         vecplus_(N-1,V1,V2,V3).
```

Functions Package: Examples – Sugar for Append

- Some syntactic sugar for append:

```
:- function append/2.
test1 :- set_prolog_flag(write_strings,on),
         X = " ",
         write(append("Hello",append(X,"world!"))).
```

- Even more:

```
:- function append/2.
:- op(200,xfy,[::]).
:- function :: /2.

A :: B := append(A,B).

test2 :- set_prolog_flag(write_strings,on),
         X = " ",
         write("Hello" :: X :: "world!").
```

Higher-Order Programming

- HO in Ciao [5] currently implemented by the family of `call/N` builtins.
- First argument of `call/N` may be instantiated to:
  - ◇ A higher-order term, supporting currying: `member([1,2])`
  - ◇ A "predicate abstraction": `(''(X,Y) :- Y is X+10)`
- Currying adapted to familiar semantic conventions in logic programs:
  - ◇ For unary higher-order predicates, the argument is added first:

    `>(0)` checks if a given number is *greater than* `0`

    `member(L)` is true if the argument is member of the list `L`
  - ◇ For binary higher-order predicates, the first argument is added first, the second one is added last:

    `append(".")` appends to the first argument the string `"."`, returning the result in the second one

    `/(2)` divides by 2 the first argument, returning the result in the second one (given the definition `/(X,Y,Z) :- Z is X/Y`)

Higher-Order Programming (Contd.): Currying Rules in Action

```
:- set_prolog_flag(multi_arity_warnings,off).

p(X,Y,Z,W,K,L) :- display(p(X,Y,Z,W,K,L)),nl.


?- use_package(hiord).

?- call(p,1,2,3,4,5,6).    -->    p(1,2,3,4,5,6)
?- call(p(1),2,3,4,5,6).  -->    p(2,1,3,4,5,6)
?- call(p(1,2),3,4,5,6).  -->    p(3,1,2,4,5,6)
?- call(p(1,2,3),4,5,6).  -->    p(4,1,2,3,5,6)
?- call(p(1,2,3,4),5,6).  -->    p(5,1,2,3,4,6)
?- call(p(1,2,3,4,5),6).  -->    p(6,1,2,3,4,5)
?- call(p(1,2,3,4,5,6)).  -->    p(1,2,3,4,5,6)
```

Higher-Order Programming (Contd.)

- Special syntax supported:
  `P(X,...)` is read as `call(P,X,...)`,
  `_(X,...)` is read as `''(X,...)`
- `meta_predicate/1` declarations extended to reflect higher-order predicates.
- Example: parametric list regular type:

```
:- prop list(L,T) + regtype # "@var{L} is a list of @var{T}s.".
:- meta_predicate list(?, pred(1)).
list([],_).
list([X|Xs], T) :-
        T(X),
        list(Xs, T).
```

- Examples of use:
  - ◇ `list(L, list(atom))` checks that a term `L` is a list of lists of atoms
  - ◇ `list(L, (_(X) :- write(X), nl))` writes all the elements of `L` !

Combining Higher-Order with Functional Notation

- They can be combined, resulting in essentially functional-style code (but sometimes with additional modes of use!).
- Some common examples (in `library(hiordlib)`):

```
:- meta_predicate map(_,pred(2),_).
map([], _) := [].
map([X|Xs], P) := [~P(X)|~map(Xs,P)].

:- meta_predicate foldl(_,_,pred(3),_).
foldl([], Seed, _Op) := Seed.
foldl([X|Xs], Seed, Op) := ~Op(X,~foldl(Xs,Seed,Op)).
```

- Example use of `map/3`: translating a list of indices to a list of terms.

```
?- map([1,3,2], arg(f(a,b,c,d)), R).
R = [a,c,b] ?
yes
```

Records package (named arguments)

- Provides named access to arguments of terms and literals.
- Example:

```
:- include(library(argnames)).

:- argnames person(name, age, profession).

p(person${}).
q(person${age=> 25}).
r(person${name=> D, profession=>prof(D),age=>age(D)}).
s(person${age=>t(25), name=> daniel}).
```

Translates to:

```
p(person(_,_,_)).
q(person(_,25,_)).
r(person(A,age(A),prof(A))).
s(person(daniel,t(25),_)).
```

Using Other Computation Rules

- Libraries which replace the depth-first, left to right computation rule of Prolog.
- Compile-time transforming programs (Compiling Control technique).
- Useful in search problems when a complete proof procedure is needed. (e.g., for teaching logic)
- Computation rules currently implemented:
  - ◇ Breadth-first (`bf` package)
  - ◇ "And-fair" breadth-first (`bf/af` package)
  - ◇ Iterative-deepening (`id` package)
  - ◇ Depth-First search with limited depth (`id` package)
  - ◇ Mycin.
  - ◇ Andorra (in Beta).

Breadth-First

- Use package `bf`.
- Predicates written with the operator ‘`<-`’ are executed using breadth-first search.
- Normal predicates and breadth-first predicates can be freely mixed in the same module.
- The `bf/af` version ensures “And-fairness” by goal shuffling.

Breadth-First Example I

```
:- module(chain, [test/1], [bf]).

test(df) :- chain(a,d).     % Loops with usual depth first rule
test(bf) :- bfchain(a,d).

bfchain(X,X) <- .
bfchain(X,Y) <- arc(X,Z), bfchain(Z,Y).

chain(X,X).
chain(X,Y):- arc(X,Z), chain(Z,Y).

arc(a,b).   arc(a,d).
arc(b,c).   arc(c,a).
```

Breadth-First Example II

```
:- module(sublist, [test/1], ['bf/af']).

test(df) :- sublist_df([a],[b]).  % loops with depth first rule.
test(bf) :- sublist_bf([a],[b]).  % loops with normal breadth-first

sublist_df(S,L) :- append(_,S,Y), append(Y,_,L).

sublist_bf(S,L) <- append(_,S,Y), append(Y,_,L).

append([], L, L) <- .
append([X|Xs], L, [X|Ys]) <- append(Xs, L, Ys).
```

Iterative-Deepening

- Modules can be marked to have iterative deepening behaviour.
- A directive sets the initial depth, the predicate that computes the increment, and, optionally, a maximum depth.

  Examples:

```
  :- iterative(p/1,5,f).   % to start with depth 5 and increment by 10
  f(X,Y) :- Y is X + 10.
                           % or, using predicate abstactions
 :- iterative(p/1,5,(_(X,Y):- Y is X + 10)).

 :- iterative(p/1,5,(_(X,Y):- Y is X + 10),100). %  All goals below
                                                 %  100 simply fail
```

- Bounded depth-first can be done by one-step iterative-deepening:

```
 :- iterative(p/1,100,f,100).
```

Constraints

- Currently two packages: `clpq` and `clpr`.
- Based on Holzbaur's implementation [19, 18] using attributed variables.
- The effect is local to a module.
- CLP($\mathcal{Q}$) is exact, CLP($\mathcal{R}$) is (obviously) approximate.
- Constraints must be written using special operators: `X .=. Y+Z`, `X .=<. 2*Y`
- Linear equations are checked for satisfiability immediately, nonlinear equations are delayed until they become linear.
- The packages are also usable directly in the toplevel:

```
?- use_package(clpq).
{ some messages }
?- X*Y .>. Z, X+2*Y .=. 10, X .=. Y/3.
X = 10/7, Y = 30/7, Z.<.300/49 ?
```

- Other constraint domains (e.g., finite domains) in development.

CLP example

- Example: placing N queens in a N*N board

```
queens(N, Qs) :- constrain_values(N, N, Qs), place_queens(N, Qs).

constrain_values(0, _N, []).
constrain_values(N, Range, [X|Xs]) :-
        N .>. 0,
        X .>. 0, X .=<. Range,
        N1 .=. N - 1,
        constrain_values(N1, Range, Xs), no_attack(Xs, X, 1).

no_attack([], _Queen, _Nb).
no_attack([Y|Ys], Queen, Nb) :-
        Queen .<>. Y,       % this line missing in the slides!!
        Queen .<>. Y+Nb,
        Queen .<>. Y-Nb,
        Nb1 .=. Nb + 1,
        no_attack(Ys, Queen, Nb1).
```

Persistent Predicates

- Persistent Predicate [10, 2]: dynamic predicate residing in non-volatile media.
- Its state survives across successive executions of the application.
- Currently supported storage media:
  - ◇ Files: `persdb` package.
  - ◇ SQL database: `persdb_sql` package.
- Usage transparent to the storage media, and similar to normal data (dynamic) predicates.
- Changes to the persistent predicates are recorded atomically and transactionally:
  - ◇ Security against possible data loss due to, for example, a system crash.
  - ◇ Allows concurrent updates from different programs.
- Update primitives analog to `assert/1` and `retract/1`.
- Transactional behaviour.

Persistent Predicates Example

- Example: persistent queue.

```
persistent_dir(queue_dir,'./DB').
:- persistent(queue/1, queue_dir).

main:- write('Action ( in(Term). | out. | halt. ): '),
       read(A),
       ( handle_action(A) -> true ; write('Unknown command.'), nl ),
       main.

handle_action(halt) :- halt.
handle_action(in(Term)) :- passertz_fact(queue(Term)), main.
handle_action(out) :-
     (  pretract_fact(queue(Term))
     -> write('Out '), write(Term)
     ;  write('FIFO empty.') ),
     nl, main.
```

Object-Oriented Features: O'Ciao

- Basic design philosophy [20]:
  - ◇ Identify desired feature(s) of OOP not present or difficult to use in LP/Ciao.
  - ◇ Add them in the most natural way.
  - ◇ Blend object model as much as possible with existing LP/Ciao concepts and features (e.g., the module system).

Feature	OOP	Correspondance in (Ciao) Prolog
State	attributes	dynamic predicates
Encapsulation	classes	modules
Polymorphism	overloading	clause selection
Instantiation	objects	–
Inheritance	classes	(reexport)

- Missing is instantiation → use module system / dynamic predicates; add:
  - ◇ Module instantiation.
  - ◇ Other features (virtual methods, interfaces, inheritance, ...).

Ciao Instantiable Modules → Classes/Objects

- `new/2`: conceptually creates a dynamic “copy” of a module.
  (But implemented more efficiently!)
- Effectively, implements a very useful notion of classes/objects.
- Example:

```
:- class(deck,[addcard/1,drawcard/1]).

:- dynamic card/2.
% initial state
card(1,hearts).
card(8,diamonds).

addcard(card(X,Y))  :- asserta(card(X,Y)).
drawcard(card(X,Y)) :- retract(card(X,Y)).
```

```
:- module(main,[main/0],[objects]).
:- use_class(deck).

main :-
     S1 new deck,
     S2 new deck,
     S1:drawcard(C),
     S2:addcard(C).
```

Ciao Instantiable Modules → Classes/Objects (Contd.)

- Same calling syntax as for the module system.
- Visibility controlled by the same rules as in the module system.
- Object state is represented by the state of the dynamic predicates.
- (Implemented basically on top of Standard Prolog.)

- Similar capabilities to other designs (e.g., SICStus objects, Logtalk, ...). But those are typically unrelated to the module structure.

O'Ciao: Defining Classes

- The `module` declaration is replaced by a `class` declaration.

  `:- class(stack).` ≡ `:- module(stack,[],[class]).`

- Predicates are interpreted as (instance) methods.

- The usual `export` declarations define the public interface of the class: the visible methods for the class instances.

  ```
  :- export(push/1).
  :- export(pop/1).
  ```

  or

  ```
  :- class(stack,[push/1,pop/1]).
  ```

- The `dynamic` and `data` declarations are the attribute declarations.

  ```
  :- dynamic storage/1.
  ```

  or

  ```
  :- data storage/1.
  ```

- Attributes are easily initialized by writing facts for them.

Another Example of a Class

```
:- class(stack,[push/1,pop/1,top/1,is_empty/0]).

% Attribute
:- data storage/1.

% Methods
push(Item) :- asserta_fact(storage(Item)).

pop(Item) :- retract_fact(storage(Item)).

top(Top) :- storage(Top), !.

is_empty :- \+ storage(_).
```

O’Ciao: Using Classes

- The `objects` package enables creating and using objects from imported classes:

```
:- use_package(objects).
```

- The `use_module` declaration is replaced by a `use_class` declaration.

```
:- use_class(stack).
```

- The `new` operator enabled by the `objects` package allows instance creation.

```
...:- ..., X new stack, ...
```

- Object identified by “instance qualification”
(resembling module qualification)

```
..., X:push(Item), ...
```

O'Ciao: Other Features

- Inheritance:
  - ◇ Obtained via extension of the reexport capabilities of the module system.
  - ◇ Some syntactic sugar provided (`inheritable/1`, `inherit_class/1`).
- Overriding:
  - ◇ Inherited methods *overridden* by new predicate declaration for them in the subclass.
  - ◇ `self/1`.
  - ◇ Follows also module system conventions.
- Abstract methods (`virtual` declarations), refinement.
- *Interfaces* used to simulate multiple inheritance (as in Java).

Active Modules / Active Objects

- Modules to which computational resources are attached.
- High-level model of client-server interaction.
- An active module is a network-wide server for the predicates it exports.
- Any module or application can be converted into an “active module” (active object) by compiling it in a special way (creates an executable with a top-level listener).
- Procedures can be imported from remote “active modules” via a simple declaration: E.g. `:- use_active_module(Name, [`P_1`/`N_1`, `P_2`/`N_2`,...]).`
- Calls to such imported procedures are executed remotely in a transparent way.
- Typical application: client-server. Client imports module which exports the functionality provided by server. Access is transparent from then on.
- Built as an abstraction on top of ports/sockets
  (also a free library for SICStus and other systems).

Using Active Modules: An Example

- Server code (active module), file `database.pl`:

```
:- module(database, [stock/2]).

stock(p1, 23).
stock(p2, 45).
stock(p3, 12).
```

- Compilation: "`ciaoc -a` *address publishing method* `database`" or:

```
?- make_actmod('/home/clip/public_html/demo/pillow/database.pl',
               'actmods/filebased_publish').
```

  produces executable called `database`.

- Active module started as a process – e.g., in unix:
  `database &`

Using Active Modules: An Example

- Client (file `sales.pl`):

```
:- module(sales,[need_to_order/1],[actmods]).
:- use_active_module(database, [stock/2]).
:- use_module(library('actmods/filebased_locate')).

need_to_order(P) :-
       stock(P, S),
       S < 20.
```

- Usage:

```
?- use_module(sales).
?- need_to_order(X).
```

Basic Concurrency

- (Low-level) Concurrency in Ciao Prolog is currently provided [9] by two sets of primitives:
  - ◇ Primitives to spawn and control independent execution threads.
  - ◇ Primitives to synchronize and share information among threads.
- Spawning-related primitives provide basic control on threads.
- Threads are flat: they offer a basic mechanism on top of which more involved formalisms (e.g., concurrent objects) are built.
- Communication/synchronization implemented through accesses to the shared database:
  - ◇ Predicates declared `concurrent` have a special regime access: calls suspend instead of failing if no matching clause exists at the time of the call.
  - ◇ Backtracking can take place after suspension.
  - ◇ All accesses and updates are atomic.
  - ◇ Other primitives can change the behavior of concurrent predicates at runtime.

A Simple Example

- Start several predicates which wait for a fact to appear.

```
:- concurrent proceed/1.

waitf:-
     retract_fact(proceed(X)),
     display(proceeding(X)),
     nl.
```

```
wait_facts:-
     eng_call(waitf, create, create),
     eng_call(waitf, create, create),
     eng_call(waitf, create, create),
     asserta_fact(proceed(1)),
     asserta_fact(proceed(2)),
     asserta_fact(proceed(3)).
```

- The `concurrent/1` directive instructs the compiler to mark `proceed/1` as a concurrent predicate: calls will *suspend* if needed.
- `wait_facts/0` starts three threads in **separate** stack sets (note the `create` parameter).
- Each of them will atomically wait for and retract a clause of the predicate.
- Threads are executed **in parallel** when using a multiprocessor machine.

A Threaded TCP/IP-based Server

- Will wait for a connection, read two numbers, add them, and return the result.
- (Several handle_conn/0 have been previously started.)

```
:- concurrent conn/1.

wait_for_queries(Socket):-
     repeat,
     socket_accept(Socket, Stream),
     assertz_fact(conn(Stream)),
     fail.
```

```
handle_conn:-
     retract_fact(conn(Stream)),
     read(Stream, Number1),
     read(Stream, Number2),
     Result is Number1 + Number2,
     write(Stream, Result),
     close(Stream),
     fail.
```

- The main loop listens on a port and asserts stream ids as connections arrive.
- Each handle_conn/0 waits for a conn/1 to appear; it gets a Stream from which numbers to add are read.
- It fails after the answer is returned ⟶ goes back to waiting for a new conn/1!

Higher-Level Concurrency Primitives

- `eng_call/3` (and others to, e.g., perform backtracking on concurrent goals) are often too low level.
- Better primitives are built on top of them (see [14, 3] for other primitives):
  - ◇ `Goal &> Handle` executes `Goal` in a separate environment, leaves a `Handle` pointing to the computation.
  - ◇ `Handle <&` waits (if necessary) for the end of the computation and installs the bindings locally.
  - ◇ Communication transparently implemented through the shared database.
- A library implementing these operators allows the programmer to write concurrent code with *arbitrary explicit* dependencies:

```
concurr:-  a &> Ha, b &> Hb, c &> Hc,
           ..., Hb <&,  ..., Ha <&, ..., Hc <&, ...
```

- And also, as a particular case, the good, old fork and join of &-Prolog:

```
A & B :- A &> Ha, B, Ha <& .
```

Distributed Execution

- It is very easy to write a server which listens on a port for goals and executes them [3] (recall the TCP/IP-based server):

```
:- concurrent conn/1.              handle_query:-
                                        retract_fact(conn(Stream)),
wait_for_queries(Socket):-              read(Stream, Goal),
     repeat,                            call(Goal),
     socket_accept(Socket, Stream),     write(Stream, Goal),
     assertz_fact(conn(Stream)),        close(Stream),
     fail.                              fail.
```

- This is a simple implementation of a *goal server* for distributed execution:
  - ◇ Clients connect to a server and send goals, keeping a local handle.
  - ◇ The server reads and executes the goals.
  - ◇ Clients, when needed, ask for answers.
  - ◇ Bindings are sent back with each answer, and are locally installed using logical variables stored in the handle.

Distributed Execution (Contd.)

- A more complete server implies a more complex negotiation: a unique identifier per remote goal, remote backtracking, remote cut. . .
- We use the syntax of [3] (extension of the high-level concurrency primitives).
- From the client point of view:

```
p(...):- ..., r(X) @ Host > Handle, ..., Handle <&, ...
```

- `Handle` encapsulates:
  - ◇ The initial `Goal` (including logical variables),
  - ◇ the `Host` we want to execute our work,
  - ◇ a unique identifier for the communication.

Active Objects, Code, and Computation Mobility

- Code mobility is easy: code just a set of Prolog terms or string of bytecode.
- Migrating active computations is heavy from an implementation point of view: need to stop the engine, save state, reinstall O.S.-dependent data structures. . .
- Easy in continuation-based systems as BinProlog (but they have other problems).
- *Migrating objects* makes sense: they have local state.
- State of *Ciao* objects: set of facts ⟶ set of Prolog terms.
- Objects can be transparently put in a *blocked* state by the *object server*: do not accept new invocations, keep track of the finished operations.
- Moving objects can performed by:
  - ◇ *Blocking* the object.
  - ◇ Sending static code (if needed) to target host + its state (dynamic code).
  - ◇ Notifying those which may want to connect to the object the new location.
- Several algorithms possible for the last point: work in progress in this area.

Web Programming

- The PiLLoW library simplifies the process of writing Internet and WWW applications [8, 4].
- Provides facilities for:
  - Generating HTML/XML structured documents by handling them as Herbrand terms (bidirectional syntax conversion).
  - Writing CGI executables.
  - Producing HTML *forms*.
  - Writing form handlers: form data parsing.
  - Accessing and parsing WWW documents.
  - Using HTML templates.
  - Handling cookies.
  - Accessing code posted at HTTP addresses.

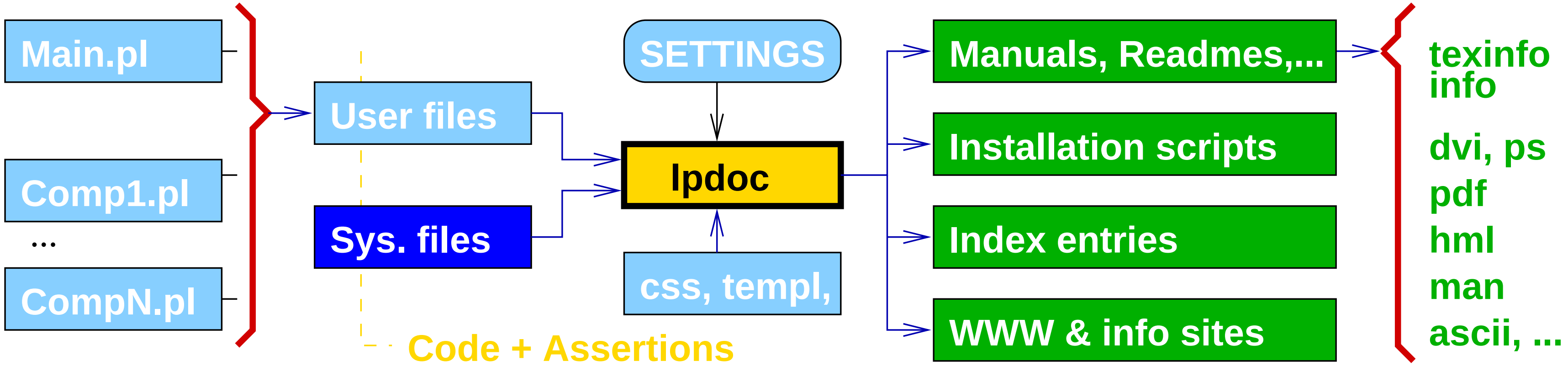
Form Producer/Handler Example

```
main(_) :-
    get_form_input(Input),
    get_form_value(Input,person_name,Name),
    response(Name,Response),
    file_to_string('html_template.html', Contents),
    html_template(Contents, HTML_terms, [response = Response]),
    output_html([cgi_reply|HTML_terms]).

response(Name, []) :- form_empty_value(Name), !.
response(Name, ['Phone number for ',b(Name),' is ',Info, --]) :-
        phone(Name,Info), !.
response(Name, ['No phone number available for ',b(Name), '.', --]).

%% Database
phone('Hanna', '613 460 069').
(...)
```

LPdoc: the Ciao Automatic Documentation System

- Writing and, specially, maintaining program documentation is hard
  → automate process as much as possible.
- Objectives:
  - Keep documentation close to source
    (easy to keep in sync with the program – “Literate Programming”).
  - Be able to *reuse* typical program documentation.
  - Integrate closely with assertion language used in debugging/verification.
  - Produce useful documentation even if no comments or assertions in program.
  - Integrate in program development environment (e.g., version control system).
  - Allow complex manuals (indices, images, citations from BiBTeX dbs, etc.).
  - Support many output formats.
  - Perform several related tasks (e.g., construction of distribution sites).
  - Allow text reuse in multiple places (e.g., manuals, readmes, distribution sites, lists of manuals and sw packages, announcements, installation scripts, ...)
  - Be largely (CLP) platform-independent and modular.

LPdoc Overall operation



- User view:
  - ◇ Creating manual:
    - * Edit `SETTINGS` file
    - * `lpdoc` *format* (`dvi`, `ps`, `html`, ...)
  - ◇ Viewing manual: `lpdoc dviview`, `lpdoc htmlview`, ...
  - ◇ Installing manual: `lpdoc install`
  - ◇ + cleanup, etc.

LPdoc Inputs

- Basic types of input files:
  - ◇ Files to be documented (possibly including assertions and comments).
  - ◇ Used but not documented (library) files
    (e.g., system and user libraries: types, properties, reexports, etc.).
  - ◇ `SETTINGS`, template files, HTML style (css files), etc.
- `SETTINGS`:
  - ◇ Determines main file and components.
  - ◇ Defines the paths to be used to find files (independent of the paths used by the `LPdoc` application itself).
  - ◇ Selects indices (predicates, ops, declarations, properties, types, libraries, concepts, authors, ...), options, etc.
  - ◇ Selects location of BiBTeX file(s), HTML styles, etc.
  - ◇ Defines installation location, etc.

Assertions

- Assertions:
  - ◇ Written in the Ciao assertion language [22].
  - ◇ Declarations, used to:
    - * state general properties, types, modes, exceptions, ...
    - * of certain program points, predicate usages, ...
  - ◇ Includes standard compiler directives (`dynamic`, `meta_predicate`, etc.).
  - ◇ Have a certain qualifier: check, true, trust, ...
  - ◇ Can include documentation text strings.
- `LPdoc` [11] understands assertions natively and uses them to generate the documentation.

Assertions (Contd.)

- Examples – pred:

```
:- pred qsort(X,Y) : list(X) => sorted(Y)
                   # "@var{Y} is a sorted permutation of @var{X}.".
```

- Examples – prop, regtype:

```
:- prop sorted(X) # "@var{X} is sorted.".
sorted([]).
sorted([_]).
sorted([X,Y|R]) :- X < Y, sorted([Y|R]).

:- regtype list(X) # "@var{X} is a list.".
list([]).
list([_|T]) :- list(T).
```

Comments

- Declarations, typically containing textual comments:

```
:- comment(CommentType,CommentData).
```

- Examples:

```
:- comment(title,"Complex numbers library").
:- comment(summary,"Provides an ADT for complex numbers.").
:- comment(ctimes(X,Y,Z),"@var{Z} is @var{Y} times @var{X}.").
```

- Markup language, close to LaTeX/texinfo:
  - ◇ Syntax: `@`*command* (followed by either a space or {}), or `@`*command*{*body*}.
  - ◇ Command set kept small and somewhat generic, to be able to generate documentation in a variety of formats.
  - ◇ Names typically the same as in LaTeX.
  - ◇ Types of commands:
    - * Indexing and referencing commands.
    - * Formatting commands.
    - * Inclusion commands, etc.

Structure of generated documents

- Overall structure:
  - ◇ Single file → simple manual without chapters.
  - ◇ Multiple files:
    - * Main file gives title, author(s), version, summary, intro, etc.
    - * Other (“component”) files are chapters and appendices.
- Chapters:
  - ◇ If file does not define `main` → assumed *library*, *interface* (API) documented. else → assumed *application*, *usage* documented.
  - ◇ Structure:
    - * Chapter title/subtitle (or file name if unavailable).
    - * Info on authors, version, copyright, ...
    - * Chapter intro.
    - * Interface (usage, exports, reexports, decls, ops, modules used, ...).
    - * Documentation for decls, preds, props, regtypes, multifiles, modedefs,...
    - * Bugs, changelog, appendices, ...

Documentation of predicates, props, etc.

- If no declarations or comments:
  - ◇ One line stating predicate name and arity (useful: goes to index → automatic location, automatic completion).
  - ◇ If property or regtype: source code (often best description).
- Comments for the predicate/property/regtype...
- All assertions, described in textual form (unless stated otherwise).
- `pred` assertions documented as “usages”.
- Comments associated with `pred` assertions used to describe the usages.
- Syntactic sugar can be kept or expanded.
- The text in properties is *reflected* into the predicates which use such properties (also if property is imported from another module).

CiaoPP: The *Ciao* System Preprocessor

- *CiaoPP* [13, 16] is a standalone preprocessor to the standard clause-level compiler.
- Performs source-to-source transformations:
  - ◇ Input: logic program (optionally w/assertions [22] & syntactic extensions).
  - ◇ Output: *error/warning messages* + *transformed logic program*, with
    - * Results of analysis (as assertions).
    - * Results of static checking of assertions [15, 21].
    - * Assertion run-time checking code.
    - * Optimizations (specialization, parallelization, etc.)
- By design, a generic tool – can be applied to other systems (e.g., CHIP → CHIPRE).
- Underlying technology:
  - ◇ Modular polyvariant abstract interpretation [1, 17].
  - ◇ Modular abstract multiple specialization [23].

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- Ciao/CiaoPP has been developed so far in collaboration with:
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Downloading the system(s)

- Downloading `ciao`, `ciaopp`, `lpdoc`, and other CLIP software:
  - ◇ Standard distributions:
    `http://www.clip.dia.fi.upm.es/Software`
  - ◇ Some betas (in testing or completing documentation – ask `webmaster` for info) in:
    `http://www.clip.dia.fi.upm.es/Software/Beta`
  - ◇ User's mailing list:
    `ciao-users@clip.dia.fi.upm.es`
    Subscribe by sending a message with only `subscribe` in the body to
    `ciao-users-request@clip.dia.fi.upm.es`
    Mail list stored in
    `http://www.clip.dia.fi.upm.es/Mail/ciao-users/`

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