Picat Tutorial

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What Is Picat?

- Why the name "PICAT"?
  - Pattern-matching, Intuitive, Constraints, Actors, Tabling
- Core logic programming concepts
  - Logic variables (arrays and maps are terms)
  - Implicit pattern-matching and explicit unification
  - Explicit non-determinism
- Language constructs for scripting and modeling
  - Functions, loops, and list comprehension
- Modules for combinatorial search
  - The `cp`, `sat`, and `mip` modules for CSPs
  - The `planner` module for planning

Niche Applications

- Scripting and Modeling
  - Constraint solving and optimization
  - Planning
  - NLP
  - Knowledge engineering
  - Complex data processing
  - Web services
  - …

Data Types

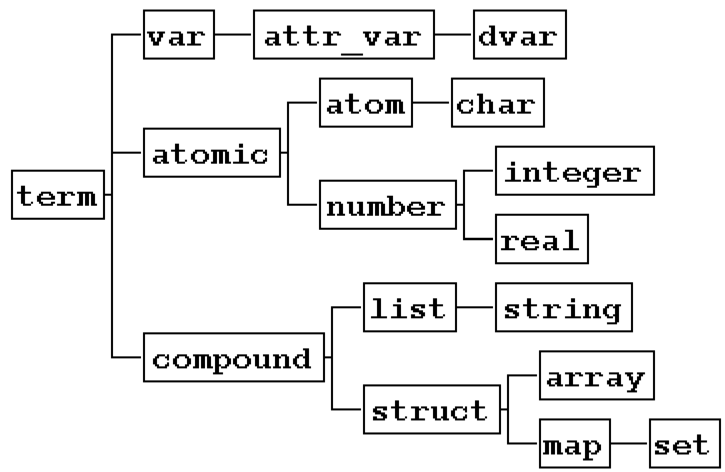
- Variables – plain and attributed

  `X1    _    _ab`

- Primitive values
  - Integer and float
  - Atom

    `x1   '_'   '_ab' '$%' '你好'`
- Compound values
  - List
    `[17,3,1,6,40]`
  - Structure
    `$triangle(0.0,13.5,19.2)`

The Type Hierarchy



Creating Structures and Lists

- Generic Structure

```
Picat> P = new_struct(point, 3)
P = point(_3b0, _3b4, _3b8)
Picat> S = $student(marry,cs,3.8)
```

- List Comprehension

```
Picat> L = [E : E in 1..10, E mod 2 != 0]
L = [1,3,5,7,9]
```

- Range

```
Picat> L = 1..2..10
L = [1,3,5,7,9]
```

- String

```
Picat> write(“hello ”++“world”)
[h,e,l,l,o,’ ’,w,o,r,l,d]
```

- Array

```
Picat> A = new_array(2,3)
A = {{_3d0, _3d4, _3d8}, {_3e0, _3e4, _3e8}}
```

- Map

```
Picat> M = new_map([alpha= 1, beta=2])
M = (map)[alpha = 1,beta = 2]
```

Special Structures

- These structures do not need to be preceded by a $ symbol
  - Patterns

    ```
    p(X+Y) => p(X), p(Y).
    ```

  - Goals

    ```
    (a, b)  (a; b)   not a    X=Y
    ```

  - Constraints and Constraint Expressions

    X+Y #= 100   X #!= 0   X #/\ Y

  - Arrays

    ```
    {2, 3, 5, 7, 11, 13, 17, 19}
    ```

Built-ins

```
Picat> integer(2)
yes
Picat> integer(2.0)
no
Picat> real(3.0)
yes
Picat> not real(3.0)
no
Picat> var(X)
yes
Picat> X = 5, var(X)
no
Picat> true
yes
Picat> fail
no
```

Built-ins (Cont.)

```
Picat> X = to_binary_string(5), Y = to_binary_string(13)
X = [‘1’, ‘0’, ‘1’]
Y = [‘1’, ‘1’, ‘0’, ‘1’]

% X is an attributed variable
Picat> put_attr(X, age, 35), put_attr(X, weight, 205), A = get_attr(X, age)
A = 35

% X is a map
Picat> X = new_map([age=35, weight=205]), put(X, gender, male)
X = map([age=35, weight=205, gender=male])

Picat> S = $point(1.0, 2.0), Name = name(S), Arity = length(S)
Name = point
Arity = 2

Picat> I = read_int(stdin) % Read an integer from standard input
123
I = 123
```

Index Notation

X[I1,…,In] : X references a compound value

```
Picat> L = [a,b,c,d], X = L[2]
X = b

Picat> S = $student(marry,cs,3.8), GPA=S[3]
GPA = 3.8

Picat> A = {{1, 2, 3}, {4, 5, 6}}, B = A[2, 3]
B = 6
```

List Comprehension

[T : E_1 in D_1, Condn , . . ., E_n in D_n, Condn]

```
Picat> L = [X : X in 1..5].
L = [1,2,3,4,5]

Picat> L = [(A,I): A in [a,b], I in 1..2].
L = [(a,1),(a,2),(b,1),(b,2)]

Picat> L = [X : I in 1..5]  % X is local
L = [_bee8,_bef0,_bef8,_bf00,_bf08]

Picat> X=X, L = [X : I in 1..5]  % X is non-local
L = [X,X,X,X,X]
```

OOP Notation

O.f(t1,…,tn)

-- means module qualified call if O is atom

-- means $f(O,t_1,…,t_n)$ otherwise.

```
Picat> Y = 13.to_binary_string()
Y = ['1', '1', '0', '1']

Picat> Y = 13.to_binary_string().reverse()
Y = ['1', '0', '1', '1']

% X becomes an attributed variable
Picat> X.put_attr(age, 35), X.put_attr(weight, 205), A = X.get_attr(age)
A = 35

%X is a map
Picat> X = new_map([age=35, weight=205]), X.put(gender, male)
X = (map)([age=35, weight=205, gender=male])

Picat> S = $point(1.0, 2.0), Name = S.name, Arity = S.length
Name = point
Arity = 2

Picat> I = math.pi    % module qualifier
I = 3.14159
```

Explicit Unification $t_1=t_2$

```
Picat> X=1                      <----------  bind
X=1
Picat> $f(a,b) = $f(a,b)        <----------  test
yes
Picat> [H|T] = [a,b,c]          <----------  matching
H=a
T=[b,c]
Picat> $f(X,Y) = $f(a,b)        <----------  matching
X=a
Y=b
Picat> $f(X,b) = $f(a,Y)        <----------  full unification
X=a
Y=b
Picat> X = $f(X)                <----------  without occur checking
X=f(f(......
```

Predicates

- Relation with pattern-matching rules

```
fib(0,F) => F=1.
fib(1,F) => F=1.
fib(N,F),N>1 => fib(N-1,F1),fib(N-2,F2),F=F1+F2.
fib(N,F) => throw $error(wrong_argument,fib,N).
```

- Backtracking (explicit non-determinism)

```
member(X,[Y|_]) ?=> X=Y.
member(X,[_|L]) => member(X,L).

Picat> member(X,[1,2,3])
X = 1;
X = 2;
X = 3;
no
```

- Control backtracking

```
Picat> once(member(X,[1,2,3]))
```

Predicate Facts

```
index(+,-) (-,+)
edge(a,b).
edge(a,c).
edge(b,c).
edge(c,b).
```

→

```
edge(a,Y) ?=> Y=b.
edge(a,Y) =>  Y=c.
edge(b,Y) =>  Y=c.
edge(c,Y) =>  Y=b.
edge(X,b) ?=> X=a.
edge(X,c) ?=> X=a.
edge(X,c) =>  X=b.
edge(X,b) =>  X=c.
```

- Facts must be ground
- A call with insufficiently instantiated arguments fails
  - `Picat> edge(X,Y)`
    `no`

Functions

- Always succeed with a return value

```
power_set([]) = [[]].
power_set([H|T]) = P1++P2 =>
    P1 = power_set(T),
    P2 = [[H|S] : S in P1].

perm([]) = [[]].
perm(Lst) = [[E|P] : E in Lst, P in perm(Lst.delete(E))].

matrix_multi(A,B) = C =>
    C = new_array(A.length,B[1].length),
    foreach(I in 1..A.length, J in 1..B[1].length)
        C[I,J] = sum([A[I,K]*B[K,J] : K in 1..A[1].length])
    end.
```

More on Functions

- Ranges are always functions

`write($f(L..U))` is the same as `Lst=L..U, write($f(Lst))`

- Index notations are always functions

`X[1]+X[2] #= 100` is the same as X1=X[1], X2=X[2], X1+X2 #= 100

`write($f(X[I]))` is the same as `Xi=X[I], write($f(Xi))`

- List comprehensions are always functions

```
sum([A[I,J] : I in 1..N, J in 1..N]) #= N*N
```

is the same as

```
L = [A[I,J] : I in 1..N, J in 1..N], sum(L) #= N*N
```

Patterns in Heads

- Index notations, ranges, dot notations, and list comprehensions cannot occur in head patterns

- As-patterns

```
merge([],Ys) = Ys.
merge(Xs,[]) = Xs.
merge([X|Xs],Ys@[Y|_])=[X|Zs],X<Y => Zs=merge(Xs,Ys).
merge(Xs,[Y|Ys])=[Y|Zs] => Zs=merge(Xs,Ys).
```

Conditional Statements

- If-then-else

```
fib(N)=F =>
 if (N=0; N=1) then
     F=1
 elseif N>1 then
     F=fib(N-1)+fib(N-2)
 else
     throw $error(wrong_argument,fib,N)
 end.
```

- Prolog-style if-then-else

```
(C -> A; B)
```

- Conditional Expressions

```
fib(N) = cond((N==0;N==1), 1, fib(N-1)+fib(N-2))
```

Assignments

- `X[I1,…,In] := Exp`
  Destructively update the component to `Exp`.
  Undo the update upon backtracking.
- `Var := Exp`
  The compiler changes it to `Var’ = Exp` and replace all subsequent occurrences of `Var` in the body of the rule by `Var’`.

```
test => X = 0, X := X + 1, X := X + 2, write(X).

test => X = 0, X1 = X + 1, X2 = X1 + 2, write(X2).
```

Loops

- Types
  - `foreach`(E$_1$ `in` D$_1$, …, E$_n$ `in` D$_n$) Goal `end`
  - `while` (Cond) Goal `end`
  - `do` Goal `while` (Cond)
- Loops provide another way to write recurrences
- A loop forms a name scope: variables that do not occur before in the outer scope are local.
- Loops are compiled into tail-recursive predicates

Scopes of Variables

- Variables that occur within a loop but not before in its outer scope are local to each iteration

```
p(A) =>
    foreach(I in 1 .. A.length)
         A[I] = $node(X)
    end.

q(L) =>
    L = [X : I in 1 .. 5].
```

```
p(A):-
    noop(X),
    foreach(I in 1 .. A.length)
         A[I] = $node(X)
    end.

q(L) =>
    noop(X),
    L = [X : I in 1 .. 5].
```

Loops (ex-1)

```
sum_list(L)=Sum =>
    S=0,
    foreach (X in L)
        S:=S+X
    end,
    Sum=S.
```

- Recurrences

$S=0$
$S_1=L[1]+S$
$S_2=L[2]+S_1$
…
$S_n=L[n]+S_{n-1}$
$Sum = S_n$

- Query

```
Picat> S=sum_list([1,2,3])
S=6
```

Loops (ex-2)

```
read_list=List =>
    L=[],
    E=read_int(),
    while (E != 0)
        L := [E|L],
        E := read_int()
    end,
    List=L.
```

- Recurrences

$L=[]$
$L_1=[e_1|L]$
$L_2=[e_2|L_1]$
…
$L_n=[e_n|L_{n-1}]$
$List=L_n$

- Query

```
Picat> L=read_list()
1 2 3
L=[3,2,1]
```

Loops (ex-3)

```
read_list=List =>
    List=L,
    E=read_int(),
    while (E != 0)
        L = [E|T],
        L := T,
        E := read_int()
    end,
    L=[].
```

- Recurrences

```
L=[e1|L1]
L1=[e2|L2]
…
Ln-1=[en|Ln]
Ln=[]
```

- Query

```
Picat> L=read_list()
1 2 3
L=[1,2,3]
```

List Comprehensions to Loops

```
List = [(A,X) : A in [a,b], X in 1..2]
```

↓

```
List = L,
foreach(A in [a,b], X in 1..2)
    L = [(A,X)|T],
    L := T
end,
L = [].
```

Tabling

- Predicates define relations where a set of facts is implicitly generated by the rules
- The process of fact generation might never end, and can contain a lot of redundancy
- Tabling memorizes calls and their answers in order to prevent infinite loops and to limit redundancy

Tabling (example)

```
table
fib(0)=1.
fib(1)=1.
fib(N)=fib(N-1)+fib(N-2).
```

- Without tabling, `fib(N)` takes exponential time in `N`
- With tabling, `fib(N)` takes linear time

Mode-Directed Tabling

- A table mode declaration instructs the system on what answers to table
  - `table(M1,M2,…,Mn)` where `Mi` is:
    - `+`: input
    - `-`: output
    - `min`: output, corresponding variable should be minimized
    - `max`: output, corresponding variable should be maximized
    - `nt`: not-tabled (only the last argument can be `nt`)
- Mode-directed tabling is useful for dynamic programming problems

Dynamic Programming (examples)

- Shortest Path

```
table(+,+,-,min)
shortest_path(X,Y,Path,W) ?=>
    Path = [(X,Y)],
    edge(X,Y,W),
shortest_path(X,Y,Path,W) =>
    Path = [(X,Z)|PathR],
    edge(X,Z,W1),
    shortest_path(Z,Y,PathR,W2),
    W = W1+W2.
```

- Knapsack Problem

```
table(+, +,-,max)
knapsack(_,0,Bag,V) =>
    Bag = [],
    V = 0.
knapsack([_|L],K,Bag,V), K>0 ?=>
    knapsack(L,K,Bag,V).
knapsack([F|L],K,Bag,V), K>=F =>
    Bag = [F|Bag1],
    knapsack(L,K-F,Bag1,V1),
    V = V1+1.
```

Modules

```
module M.
import M1,M2,…,Mn.
```

- The declared module name and the file name must be the same
- Files that do not begin with a module declaration are in the global module
- Atoms and structure names are global
- Picat has a global symbol table for atoms, a global symbol table for structure names, and a global symbol table for modules
- Each module has its own symbol table for the public predicates and functions

Modules (Cont.)

- Binding of normal calls to their definitions occurs at compile time
  - The compiler searches modules in the order that they were imported
- Binding of higher-order calls to their definitions occurs at runtime.
  - The runtime system searches modules in the order that they were loaded
- The environment variable `PICATPATH` tells where the compiler or runtime system searches for modules

Modules (Cont.)

- No module variables are allowed

  Recall that `M.f(…)` stands for `f(M,…)` if `M` is a variable

- No module-qualified higher-order calls

Modules (example)

```
% In file qsort.pi
module qsort.
sort([]) = [].
sort([H|T]) = sort([E : E in T, E <= H) ++ [H] ++ sort([E : E in T, E > H).


% In file isort.pi
module isort.
sort([]) = [].
sort([H|T]) = insert(H, sort(T)).

private
insert(X,[]) = [X].
insert(X,Ys@[Y|_]) = Zs, X=<Y => Zs=[X|Ys].
insert(X,[Y|Ys]) = [Y|insert(X,Ys)].

% another file test_sort.pi
import qsort,isort.

sort1(L)=S =>
   S=sort(L).
sort2(L)=S =>
   S=qsort.sort(L).
sort3(L)=S =>
   S=isort.sort(L).
```

The `planner` Module

- Useful for solving planning problems
  - `plan`(State,Limit,Plan,PlanCost)
  - `best_plan`(State,Limit,Plan,PlanCost)
  - …
- Users only need to define `final/1` and `action/4`
  - `final`(State) is true if State is a final state
  - `action`(State,NextState,Action,ActionCost) encodes the state transition diagram
- Uses the early termination and resource-bounded search techniques to speedup search

Ex: The Farmer's Problem

```
import planner.

go =>
    S0=[s,s,s,s],
    best_plan(S0,Plan),
    writeln(Plan).

final([n,n,n,n]) => true.

action([F,F,G,C],S1,Action,ActionCost) ?=>
    Action=farmer_wolf,
    ActionCost = 1,
    opposite(F,F1),
    S1=[F1,F1,G,C],
    not unsafe(S1).
…
```

Constraints

- Picat can be used for constraint satisfaction and optimization problems
- Constraint Problems
  - Generate variables
  - Generate constraints over the variables
  - Solve the problem, finding an assignment of values to the variables that matches all the constraints
- Picat can be used as a modeling language for CP, SAT, LP/MIP
  - Loops are helpful for modeling

Constraints (example)

- SEND + MORE = MONEY

```
import cp.

go =>
      Vars=[S,E,N,D,M,O,R,Y], % generate variables
      Vars :: 0..9,           % define the domains
      all_different(Vars),    % generate constraints
      S #!= 0,
      M #!= 0,
      1000*S+100*E+10*N+D+1000*M+100*O+10*R+E
               #= 10000*M+1000*O+100*N+10*E+Y,
      solve(Vars),            % search
      writeln(Vars).
```

N-Queens Problem

```
import cp.

queens(N) =>
    Qs=new_array(N),
    Qs :: 1..N,
    foreach (I in 1..N-1, J in I+1..N)
        Qs[I] #!= Qs[J],
        abs(Qs[I]-Qs[J]) #!= J-I
    end,
    solve(Qs),
    writeln(Qs).
```

Action Rules

- Syntax

  Head, Condition, {EventSet} => Action

  - ***Agent***

    `p(X1,…,Xn)`

  - ***Condition***
    - Inline tests (e.g., `var(X),nonvar(X),X==Y,X>Y`)
  - ***EventSet***
    - `event(X,O)` -- a general form event
    - `ins(X)` -- `X` is instantiated
    - `dom(X,E)` – An inner element E of X's domain is excluded
    - `dom_any(X,E)` -- An arbitrary element E is excluded
  - ***Action***
    - Same as a rule body

Applications of AR

- Co-routining and concurrency
  - freeze(X,Call) is compiled to AR
- Constraint propagation
  - Constraints in the cp module are compiled to AR
  - Users can program problem-specific propagators for global constraints
- Compiling CHR
- Interactive graphical user interfaces

Implementing freeze(X,Goal)

```
freeze(X,q(X,Y)))
```

↓

```
freeze_q(X,Y),var(X),{ins(X)} => true.
freeze_q(X,Y) => q(X,Y).
```

Event-Handling

```
echo(X),{event(X,O)}=> writeln(O).
```

```
Picat> echo(X), X.post_event(hello).
hello

Picat> echo(X), repeat, X.post_event(hello), nl, fail.
hello

hello

hello
…
```

Programming Constraint Propagators

- Maintaining arc consistency for aX=bY+c

```
    'aX in bY+c_arc'(A,X,B,Y,C),var(X),var(Y),
         {dom(Y,Ey)}
         =>
         T = B*Ey+C,
         Ex = T//A,
         (A*Ex==T -> fd_set_false(X,Ex);true).
   'aX in bY+c_arc'(A,X,B,Y,C) => true.
```

Whenever an element Ey is excluded from Y's domain, exclude Ey's counterpart, Ex, from X's domain.

Higher-Order Calls

- Functions and predicates that take calls as arguments
- `call(S,A1,…,An)`
  - Calls the named predicate with the specified arguments
- `apply(S,A1,…,An)`
  - Similar to call, except apply returns a value
- `findall(Template, Call)`
  - Returns a list of all possible solutions of `Call` in the form `Template`. `findall` forms a name scope like a loop.

```
Picat> C = $member(X), call(C, [1,2,3])
X = 1;
X = 2;
X = 3;
no

Picat> L = findall(X, member(X, [1, 2, 3]))
L = [1,2,3]
```

Higher-Order Functions

```
map(_F,[]) = [].
map(F,[X|Xs])=[apply(F,X)|map(F,Xs)].

map2(_F,[],[]) = [].
map2(F,[X|Xs],[Y|Ys])=[apply(F,X,Y)|map2(F,Xs,Ys)].

fold(_F,Acc,[]) = Acc.
fold(F,Acc,[H|T])=fold(F, apply(F,H,Acc),T).
```

Using Higher-Order Calls is Discouraged

- List comprehensions are significantly faster than higher-order calls
  - X `map(-,L)`
  - O `[-X : X in L]`
  - X `map2(+,L1,L2)`
  - O `[X+Y : {X,Y} in zip(L1,L2)]`

Global Maps

- `get_heap_map()`
  - Created on the heap after the thread is created
  - Changes are undone when backtracking
- `get_global_map()`
  - Created in the global area when Picat is started
  - Changes are not undone when backtracking
- `get_table_map()`
  - Created in the table area when Picat is started
  - Keys and values are hash-consed
  - Changes are not undone when backtracking

Pros and Cons of Global Maps

- Pros
  - Allows data to be accessed everywhere without being passed as arguments
  - Maps returned by `get_global_map()` and `get_table_map()` can be used to store global data that are shared by multiple branches of a search tree
    - Used in the implementation of `minof` and `maxof`.
- Cons
  - Affects locality of data and readability of programs

Global Heap Maps and Global Maps (example)

```
go ?=>
    get_heap_map().put(one,1),
    get_global_map().put(one,1),
    fail.
go =>
    if (get_heap_map().has_key(one)) then
       writef("heap map has key%n")
    else
       writef("heap map has no key%n")
    end,
    if (get_global_map().has_key(one)) then
       writef("global map has key%n")
    else
       writef("global map has no key%n")
    end.
```

Picat Vs. Prolog

- Picat is arguably more expressive

```
qsort([])=[].
qsort([H|T])=qsort([E : E in T, E=<H])++[H]++qsort([E : E in T, E>H]).

power_set([]) = [[]].
power_set([H|T]) = P1++P2 =>
    P1 = power_set(T),
    P2 = [[H|S] : S in P1].

matrix_multi(A,B) = C =>
    C = new_array(A.length,B[1].length),
    foreach(I in 1..A.length, J in 1..B[1].length)
        C[I,J] = sum([A[I,K]*B[K,J] : K in 1..A[1].length])
    end.
```

Picat Vs. Prolog

- Picat is more scalable because pattern-matching facilitates indexing rules

L ::= (“abcd”| “abc” | “ab” | “a”)*

```
p([a,b,c,d|T]) => p(T).
p([a,b,c|T]) => p(T).
p([a,b|T]) => p(T).
p([a|T]) => p(T).
p([]) => true.
```

Picat Vs. Prolog

- Picat is arguably more reliable than Prolog
  - Explicit unification and nondeterminism
  - Functions don't fail (at least built-in functions)
  - No cuts or dynamic predicates
  - No operator overloading
  - A simple static module system

Summary

- Picat is a hybrid of LP, FP and scripting
- Picat or Copycat?
  - Prolog (in particular B-Prolog), Haskell, Scala, Mercury, Erlang, Python, Ruby, C-family (C++, Java, C#), OCaml,…
- The first version is available at picat-lang.org
  - Reuses a lot of B-Prolog's code
- Supported modules
  - basic, io, sys, math, os, cp, sat, and util
- More modules will be added

Resources

- Users' Guide
  - http://picat-lang.org/download/picat_guide.pdf
- Picat Book
  - http://www.springer.com/us/book/9783319258812
- Hakan Kjellerstrand's Picat Page
  - http://www.hakank.org/picat/
- Examples
  - http://picat-lang.org/download/exs.pi
- Modules
  - http://picat-lang.org/modules.html