OCaml: The Basics

Concepts of Programming Languages
Lecture 2

CAS CS 320

Announcements

- You must attend **both** the in-class quizzes
- We will follow the online book: *OCaml Programming: Correct + Efficient + Beautiful*
- Hope you all have installed OCaml

Outline

- » Briefly outline the use of **Dune**
- » Cover the **basic expressions** we need to start programming in OCaml, look at some examples
- » Define more carefully the notion of an **inference rule**
- » Write basic OCaml programs on primitive types

Recall: Expressions

In OCaml and (functional languages in general), **everything is an expression**

Functions, variables, arguments, assignments, etc.

All expressions have a value

$$2 + (2 * 3)$$

if x = 3 then 4 else 5

$$H(f(f(f(x, y), 2), g(z)))$$

An OCaml Program is an Expression

Therefore, it has a type
And a value

For every possible expression, we'll define the syntax rules, the typing rules, and the semantic rules

Working with OCaml

Dune

Dune

`Dune is a build tool for OCaml`

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It allows us to specify project-level dependencies and configurations

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Cheatsheet:

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- **dune build:** type check your project

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- **dune utop:** open Utop in a project aware way

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- **dune build:** type check your project
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- **dune test:** run a testing code associated with the project

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- **dune build:** type check your project
- **dune utop:** open Utop in a project aware way
- **dune test:** run a testing code associated with the project
- **dune exec PROJ_NAME:** run the executable of your project

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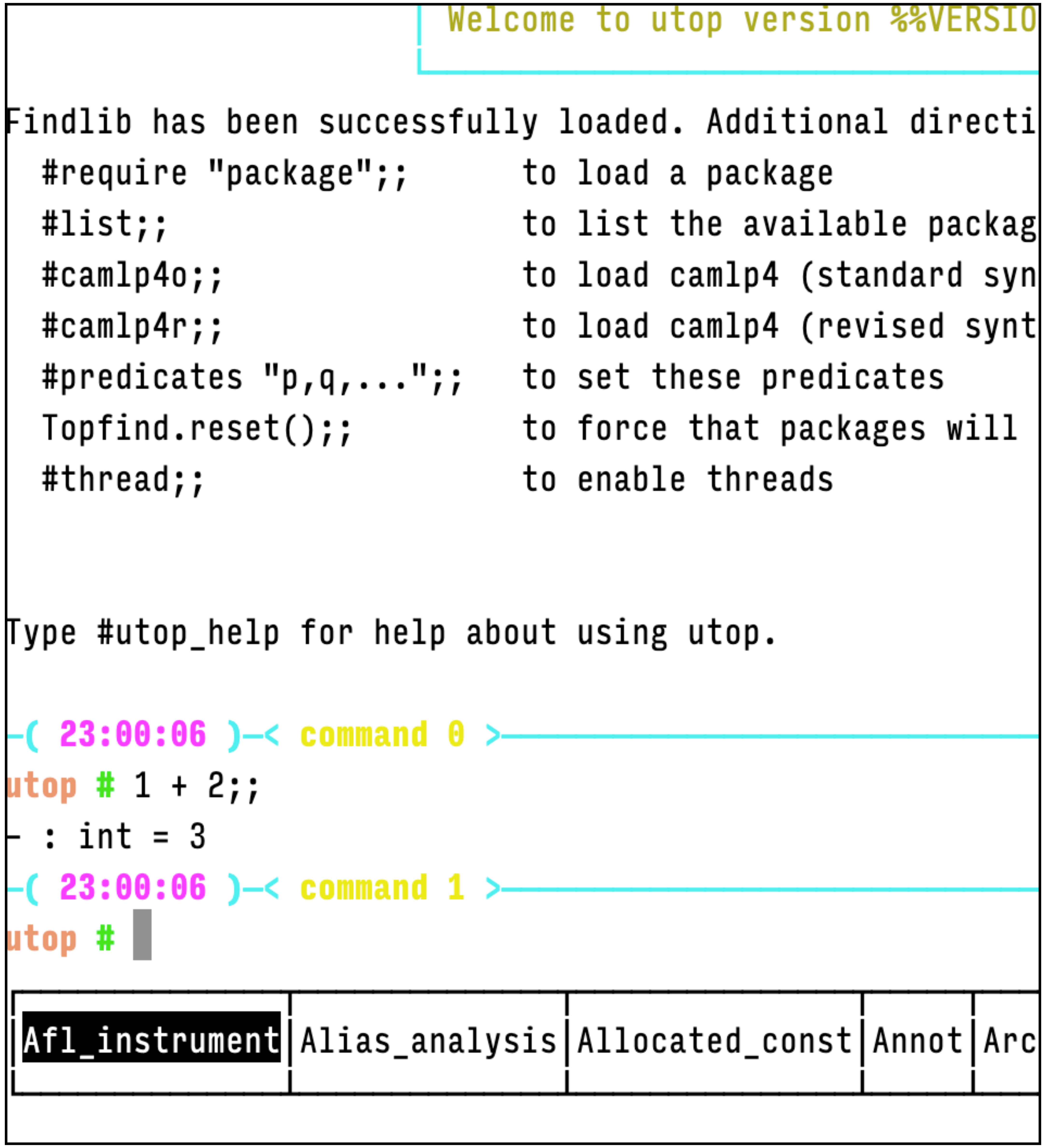
Cheatsheet:

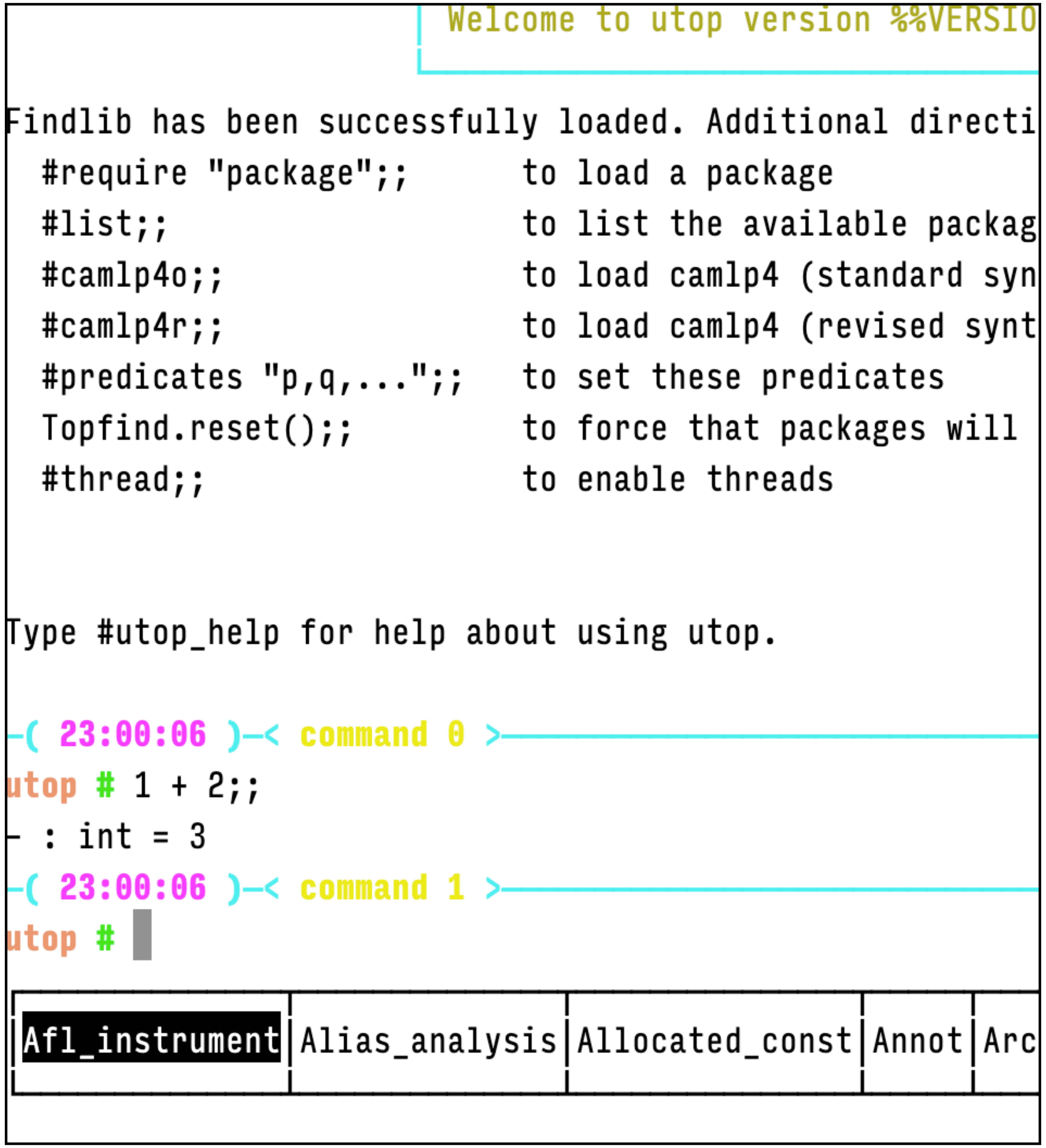
- **dune build:** type check your project
- **dune utop:** open Utop in a project aware way
- **dune test:** run a testing code associated with the project
- **dune exec PROJ_NAME:** run the executable of your project
- **dune clean:** removes files created by dune build (not so important but may come in handy)

UTop


Welcome to utop version %%VERSIO
Findlib has been successfully loaded. Additional directi
#require "package";; to load a package
#list;; to list the available packag
#camlp4o;; to load camlp4 (standard syn
#camlp4r;; to load camlp4 (revised synt
#predicates "p,q,...";; to set these predicates
Topfind.reset();; to force that packages will
#thread;; to enable threads
Type #utop_help for help about using utop.
(23:00:06)< command 0 >
utop # 1 + 2;;
- : int = 3
(23:00:06)< command 1 >
utop #
Afl_instrument
Alias_analysis
Allocated_const
Annot
Arc

UTop

UTop is an interface for the OCaml toplevel (use `utop` in terminal)



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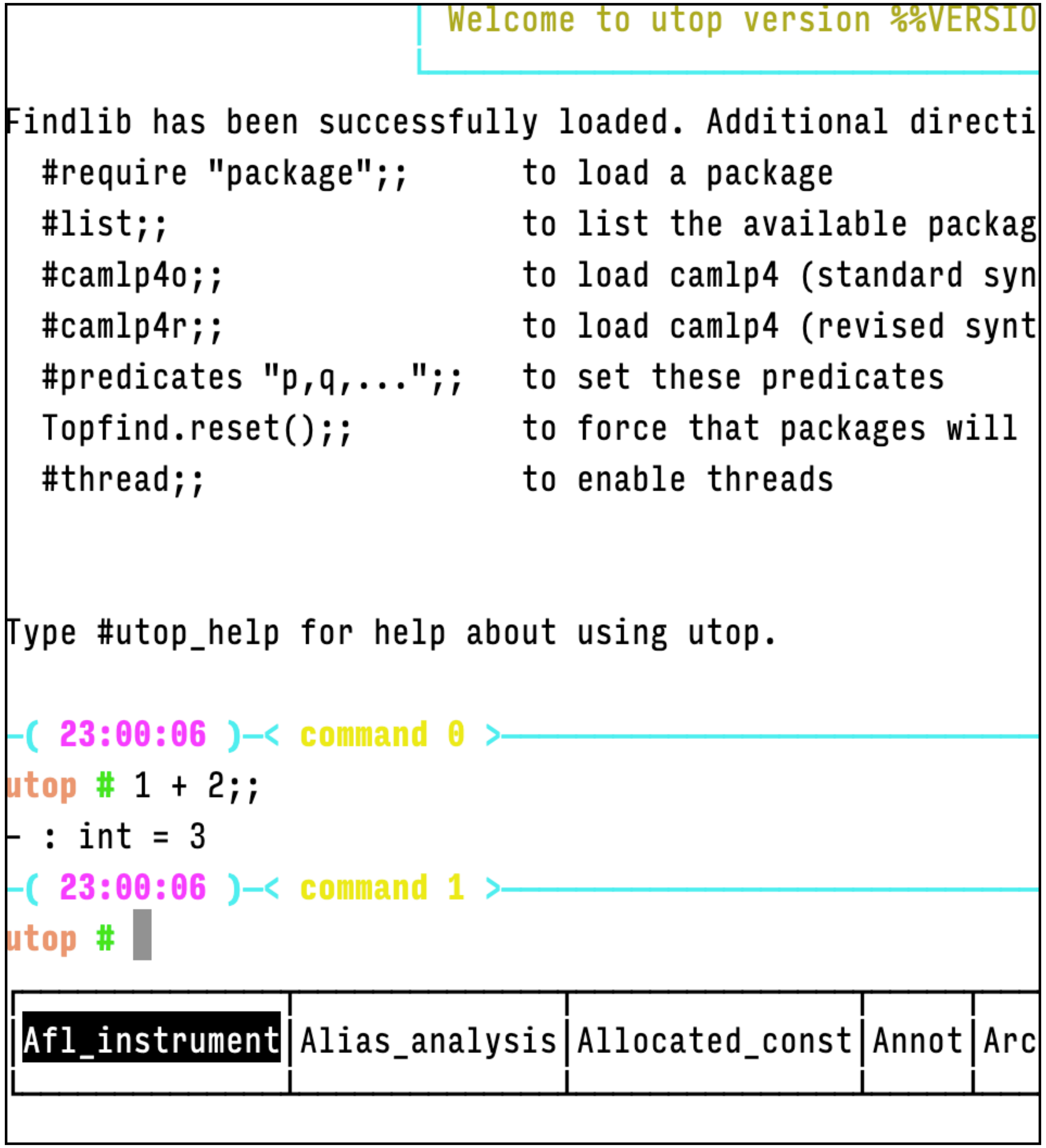

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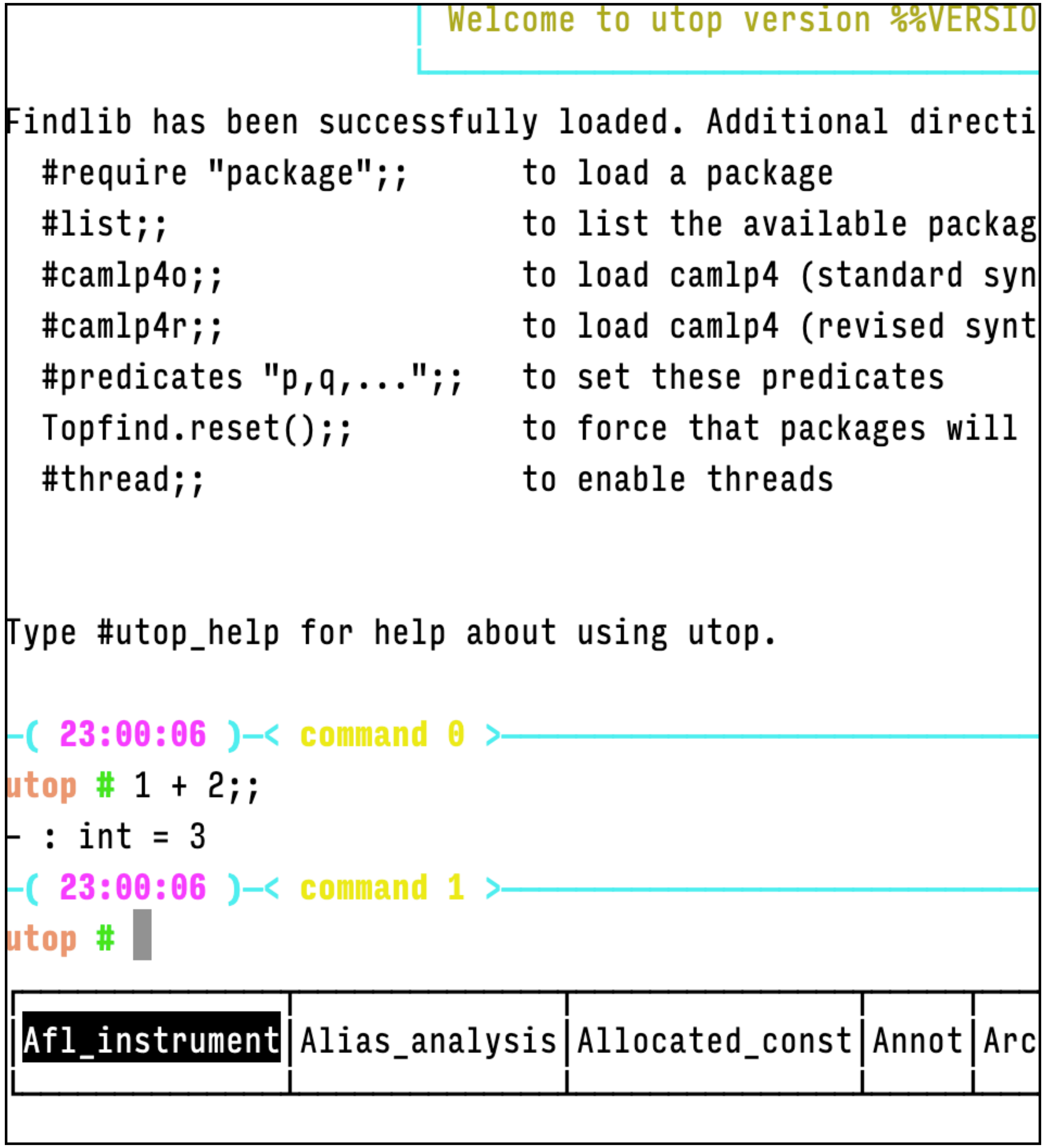

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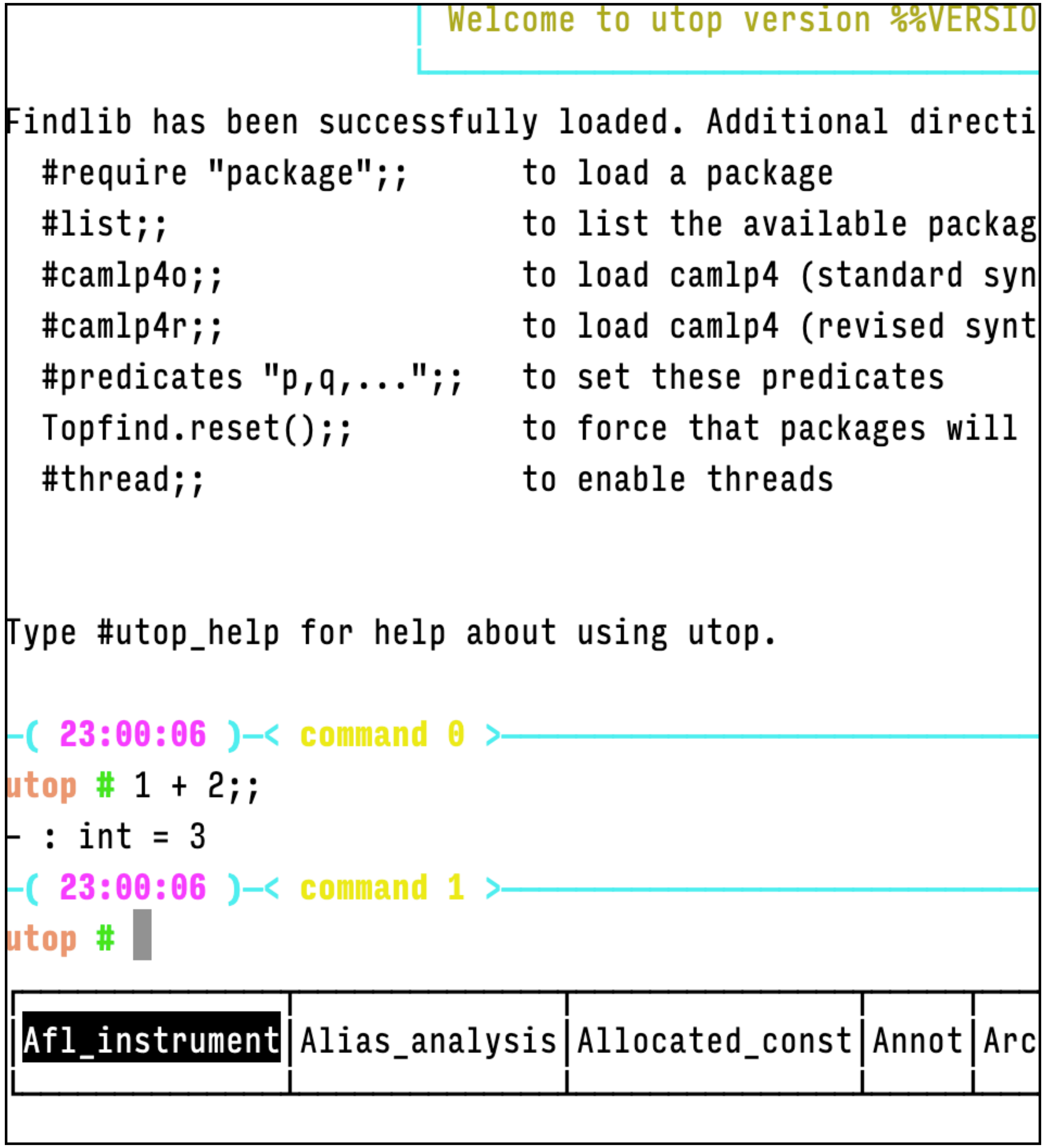
<u>Cheatsheet:</u>

- expressions must be followed with two semicolons



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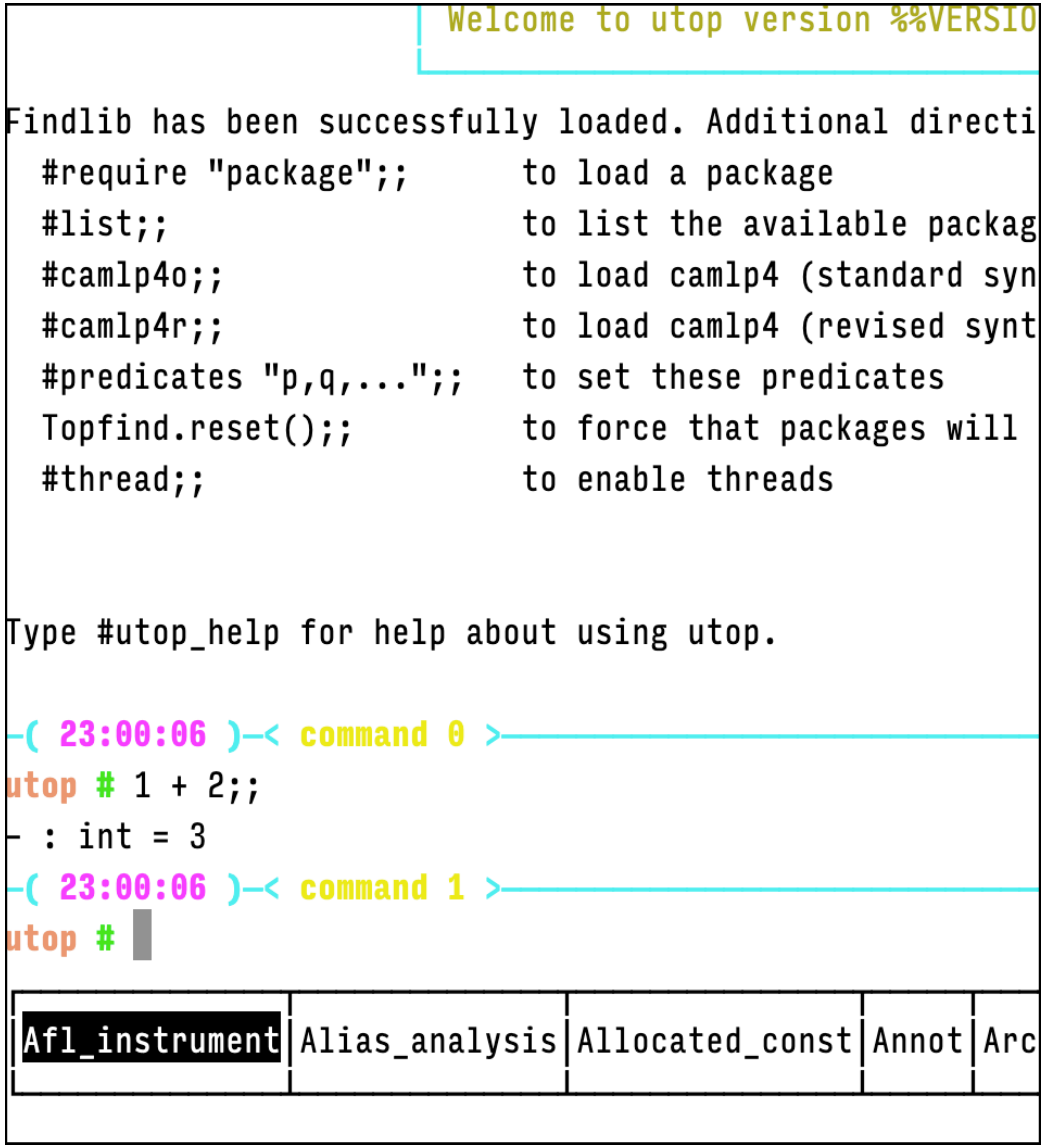
It's basically an **OCaml calculator.** It can *evaluate* OCaml expressions (useful for debugging)

Cheatsheet:

- expressions must be followed with two semicolons
- #quit;; or (Ctl-D) leaves UTop



Expressions (Informally)

High Level View

Each expression has a **form**
(e.g. 2 + 7, true, “true”)
[defined by **syntax rules**]

Each expression has a **unique type**
(e.g. 2 + 7 : int, true : bool, “true” : string)
[defined by typing rules]

Each expression has a **unique value**
(e.g. 2 + 7 $\Downarrow$ 9, true $\Downarrow$ true, “true” $\Downarrow$ “true”)
[defined by semantics rules]

Primitive Types and Literals

As with any PL, OCaml has a collection of standard types and literals

Type	Literals	Operators
int	0, -2, 13, -023	+, -, *, /, mod
float	3., -1.01	+., -., *., /.
bool	true, false	&&, ll, not
char	'b', 'c'	
string	"word", "@*&#"	^

demo

(simple use of primitive types)

A Couple Notes on Operators

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`Operators for int and float are` *`different`*`,`
`e.g.``, + (integer addition) and +. (float addition)`

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Comparison operators are standard, e.g., <, <=, >, >=, and can be used to compare any expressions of the same type

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Comparison operators are standard, e.g., `<`, `<=`, `>`, `>=`, and can be used to compare any expressions of the same type

Note that equality check is just `=` (not `==`) and inequality is `<>` (not `!=`)

A Note on Type Annotations

```
let x : int = 2 + 7
let y : bool = true
let z : string = “true"
```

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let x : int = 2 + 7
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OCaml has <u>type inference</u> which means we rarely have to *specify* the types of expression in our program

A Note on Type Annotations

```
let x : int = 2 + 7
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```

OCaml has <u>type inference</u> which means we rarely have to *specify* the types of expression in our program

That said, you **should** include type annotations, especially at the beginning, because they're useful for *documentation* and for *code clarity*

First Abstraction of the Day

Let Expressions and Variables

Let Expressions and Variables

body

```
let x = 2 in x + x
```

Let Expressions and Variables

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As with any reasonable PL, we can define local variables in OCaml

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This is useful for writing better abstractions

Note that it reads like a sentence: *let x stand for 2 in the expression x + x*

Multiple Local Variables

```
let x_squared = x * x in
let y_squared = y * y in
x_squared + y_squared
```

It's very easy to use multiple local variables, we just *nest* local variables

(If it helps, think of in as a semicolon ;)

IMPORTANT: let x = e1 in e2 is an *expression* so it can be the body of a let expression.

Let Expressions (Informal)

$$\boxed{\texttt{let x = 2 in } \underbrace{\texttt{x + x}}_{\text{body}}}$$

Let Expressions (Informal)

$\overbrace{\texttt{x + x}}^{\text{body}}$

```
let x = 2 in x + x
```

syntax: `let VARIABLE = EXPRESSION in BODY`

Let Expressions (Informal)

body

```
let x = 2 in x + x
```

syntax: `let VARIABLE = EXPRESSION in BODY`

typing: *compute type of* `EXPRESSION`*; assume* `VARIABLE` *has that type; compute type of* `BODY`

Let Expressions (Informal)

body

```
let x = 2 in x + x
```

syntax: `let VARIABLE = EXPRESSION in BODY`

typing: *compute type of* `EXPRESSION`*; assume* `VARIABLE` *has that type; compute type of* `BODY`

semantics: *compute value of* `EXPRESSION`*; substitute that value for* `VARIABLE` *in* `BODY`

Syntax Examples

Syntax Examples

body

```
let x = 2 in x + x
```

Syntax Examples

body

```
let x = 2 in x + x
```

body

```
let x = true in if x then 3 else 4
```

Syntax Examples

```
let x = 2 in x + x
```

body

```
let x = true in if x then 3 else 4
```

body

```
let x = 3.5 in 2. *. x
```

body

Syntax Examples

body

```
let x = 2 in x + x
```

body

```
let x = true in if x then 3 else 4
```

body

```
let x = 3.5 in 2. *. x
```

body body

```
let y = (let x = 2 in x + x) in 4 * y
```

Example: Ill-Typed Let-Expression

```
let x = 2. in 3 + x
```

An ill-typed expression will throw a type error when you type it into utop

Note that the body of a let-expression may be ill-typed *depending on the value assigned to its variable*

Semantics Examples

Semantics Examples

`let x = 2 in x + x` ⟶ `2 + 2`

Semantics Examples

```
let x = 2 in x + x
```

→

```
2 + 2
```

```
let x = true in
if x then 3 else 4
```

→

```
if true then 3 else 4
```

Semantics Examples

```
let x = 2 in x + x
```

$\longrightarrow$

```
2 + 2
```

```
let x = true in
if x then 3 else 4
```

$\longrightarrow$

```
if true then 3 else 4
```

Formally, we write $[v/x]e$ to mean "substitute v for x in e", e.g., $[3/x](x+x)$ is the same as $3+3$

Semantics Examples

```
let x = 2 in x + x
```
⟶
```
2 + 2
```

```
let x = true in
if x then 3 else 4
```
⟶
```
if true then 3 else 4
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Formally, we write $[v/x]e$ to mean "substitute v for x in e", e.g., $[3/x](x+x)$ is the same as $3+3$

Intuitively, substitution is simple: **replace the variable**

Semantics Examples

```
let x = 2 in x + x
```

$\longrightarrow$

```
2 + 2
```

```
let x = true in
if x then 3 else 4
```

$\longrightarrow$

```
if true then 3 else 4
```

Formally, we write $[v/x]e$ to mean "substitute v for x in e", e.g., $[3/x](x+x)$ is the same as $3+3$

Intuitively, substitution is simple: **replace the variable**

Turns out, this is **very hard** to do correctly, *it's subtle* and a source of a lot of mistakes in PL implementations

demo

(simple use of lets)

Second Abstraction of the Day

If Expressions

If-Expressions

```
if x > 0 then x else -x
```

```
if x <> y then x+y else x-y
```

If-Expressions

```
if x > 0 then x else -x
```

```
if x <> y then x+y else x-y
```

As with any reasonable PL, OCaml has expressions for doing conditional reasoning

If-Expressions

```
if x > 0 then x else -x
```

```
if x <> y then x+y else x-y
```

As with any reasonable PL, OCaml has expressions for doing conditional reasoning

Note: The **else** case is *required* and the **then** and **else** cases must be the *same type* (why?)

If-Expressions

```
if x < 0 then
  "negative"
else if x = 0 then
  "zero"
else
  "positive"
```

Answer: Remember, all we have is expressions. So every if-expression must have a value and a type (and therefore, an **else** case of the same type)

We can do **else if** just by nesting if-expressions! (neat)

If-Expressions (Informal)

```
if x > 0 then x else -x
```

If-Expressions (Informal)

```
if x > 0 then x else -x
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Syntax: `if CONDITION then TRUE–CASE else FALSE–CASE`

If-Expressions (Informal)

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Typing: `CONDITION` *must be a Boolean; compute the types of* `TRUE–CASE` *and* `FALSE–CASE`*; must be the same type; expression type is same as that of* `TRUE–CASE` *and* `FALSE–CASE`

If-Expressions (Informal)

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Typing: `CONDITION` *must be a Boolean; compute the types of* `TRUE–CASE` *and* `FALSE–CASE`*; must be the same type; expression type is same as that of* `TRUE–CASE` *and* `FALSE–CASE`

Semantics: *If* `CONDITION` *evaluates to true; evaluate* `TRUE–CASE`*, else evaluate* `FALSE–CASE`

demo

(simple use of ifs)

Third (and Most Important) Abstraction of the Day

Functions

Functions (Informal)

body

```
fun x -> x + 1
```

Syntax: `fun VARIABLE -> EXPRESSION`

Typing: `assume VARIABLE has type` **T1**`; compute the type of EXPRESSION; suppose it is` **T2**`; type of function is` **T1 -> T2**

Semantics: `A function is a value; evaluates to itself`

Functions are also Expressions

body

```
fun x -> 3 + x
```

body

```
fun y -> 2. *. x
```

body

```
fun x y z -> if x then y else z
```

body

```
fun x -> if x > 0 then x else -x
```

In OCaml, we can define *anonymous functions*, which are just **functions without names**

We Can Give them Names using Let

body

```
let f = fun x -> 3 + x
```

body

```
let g = fun y -> 2. *. x
```

body

```
let h = fun x y z -> if x then y else z
```

body

```
let abs = fun x -> if x > 0 then x else -x
```

Another Way to Define Functions

```
let abs = fun x -> if x > 0 then x else -x
```

```
let h = fun x y z -> if x then y else z
```

Another Way to Define Functions

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```
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```

```
let h x y z = if x then y else z
```

Another Way: Curried Functions

```
let h = fun x y z -> if x then y else z
```

```
let h = fun x -> fun y -> fun z -> if x then y else z
```

Another way of thinking about functions:

The only kind of function we have is *single argument*

This seems restrictive, but ultimately it doesn't affect us at all

We can *simulate* multi-argument functions with nested functions. This is called **Currying** after Haskell Curry

Curried Functions Return Functions

```
let f = fun x -> fun y -> fun z -> x + y + z
```

We should think of the above function as something which takes an input and returns **another function**

In other words, we *partially apply* the function

Application

```
(fun x -> fun y -> x + y + 1) 3 2
```

Application is done by *juxtaposition* which means we put the arguments next to the function

Application is *left-associative*, which means we pass arguments from left to right

Application (Informally)

```
(fun x -> fun y -> x + y + 1) 3 2
```

Application (Informally)

```
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```

Syntax: FUNCTION–EXPR ARG–EXPR

Application (Informally)

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(fun x -> fun y -> x + y + 1) 3 2
```

Syntax: FUNCTION–EXPR ARG–EXPR

Typing: *compute type of* FUNCTION–EXPR*; say it is* **T1 –> T2***; compute type of* ARG–EXPR*; it must be* **T1***; then the type of expression is* **T2**

Application (Informally)

```
(fun x -> fun y -> x + y + 1) 3 2
```

Syntax: FUNCTION-EXPR ARG-EXPR

Typing: *compute type of* FUNCTION-EXPR*; say it is* **T1 -> T2***; compute type of* ARG-EXPR*; it must be* **T1***; then the type of expression is* **T2**

Semantics: Evaluate ARG-EXPR; substitute its value into the body of FUNCTION-EXPR; evaluate the result

Application (Example)

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2
```

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2
```

is the same as

```
(fun x -> (fun y -> x + y  + 1)) 3  2
```

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2
```

is the same as

```
(fun x -> (fun y -> x + y  + 1)) 3  2
```

is the same as

```
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```

Application (Example)

(fun x -> fun y -> x + y + 1) 3 2 *is the same as*

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Application (Example)

(fun x -> fun y -> x + y + 1) 3 2 *is the same as*

(fun x -> (fun y -> x + y + 1)) 3 2 *is the same as*

((fun x -> (fun y -> x + y + 1)) 3) 2 *evaluates to*

(fun y -> 3 + y + 1) 2

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2        is the same as

(fun x -> (fun y -> x + y  + 1)) 3  2        is the same as

((fun x -> (fun y -> x + y  + 1)) 3) 2       evaluates to

          (fun y -> 3 + y  + 1)     2
```

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2            is the same as

(fun x -> (fun y -> x + y  + 1)) 3  2            is the same as

((fun x -> (fun y -> x + y  + 1)) 3) 2           evaluates to

          (fun y -> 3 + y  + 1)     2            evaluates to

                    3 + 2  + 1
```

is the same as / *is the same as* / *evaluates to* / *evaluates to*

Application (Example)

```
(fun x ->  fun y -> x + y  + 1)  3  2        is the same as

(fun x -> (fun y -> x + y  + 1)) 3  2        is the same as

((fun x -> (fun y -> x + y  + 1)) 3) 2       evaluates to

(fun y -> 3 + y  + 1)     2                  evaluates to

3 + 2  + 1                                   is the same as

(3 + 2) + 1
```

Application (Example)

(fun x -> fun y -> x + y + 1) 3 2	*is the same as*
(fun x -> (fun y -> x + y + 1)) 3 2	*is the same as*
((fun x -> (fun y -> x + y + 1)) 3) 2	*evaluates to*
(fun y -> 3 + y + 1) 2	*evaluates to*
3 + 2 + 1	*is the same as*
(3 + 2) + 1	*evaluates to*
5 + 1	

Application (Example)

(fun x -> fun y -> x + y + 1) 3 2	*is the same as*
(fun x -> (fun y -> x + y + 1)) 3 2	*is the same as*
((fun x -> (fun y -> x + y + 1)) 3) 2	*evaluates to*
(fun y -> 3 + y + 1) 2	*evaluates to*
3 + 2 + 1	*is the same as*
(3 + 2) + 1	*evaluates to*
5 + 1	*evaluates to*
6	

demo

(anonymous and curried functions)

Summary

OCaml is a language of **expressions**, everything is an expression

OCaml has everything we need to do basic programming