Course Introduction

Concepts of Programming Languages
Lecture 1

CAS CS 320

Outline

- Give an overview of what PL is about
- Take a first look at OCaml

What is a PL?

Fair Question

How would you define a PL?

How would you explain it to your roommate?

How would you answer if you were asked during an interview?

Discuss this with the people around you for 1min

Programmer's view of a PL

```python
def subtraction():
    num_1 = randint(0,9)
    num_2 = randint(0,9)

    print(f"What is {num_1} - {num_2} ?\n")

    choice = input("> ")

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def multiplication():
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Programmer's view of a PL

» A tool for programming

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Programmer's view of a PL

- » A tool for programming
- » A text-based way of interacting with hardware/a computer

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Programmer's view of a PL

- » A tool for programming
- » A text-based way of interacting with hardware/a computer
- » A way of organizing and working with data

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Programmer's view of a PL

» A tool for programming

» A text-based way of interacting with hardware/a computer

» A way of organizing and working with data

This is not what the course is about

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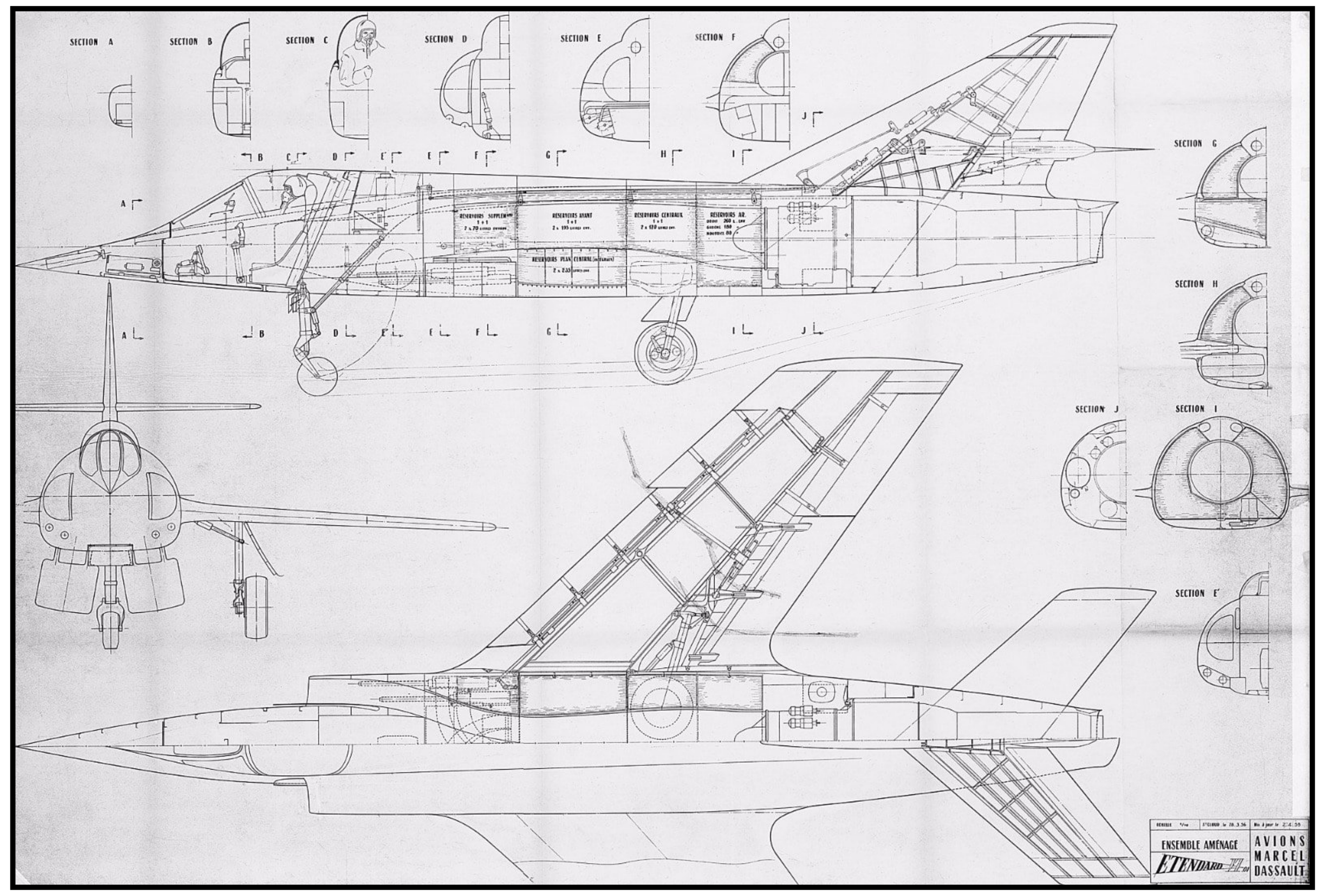
Users vs. Designers

vs.



Users vs. Designers

Programmers *use* PLs. We're interested in **designing** PLs

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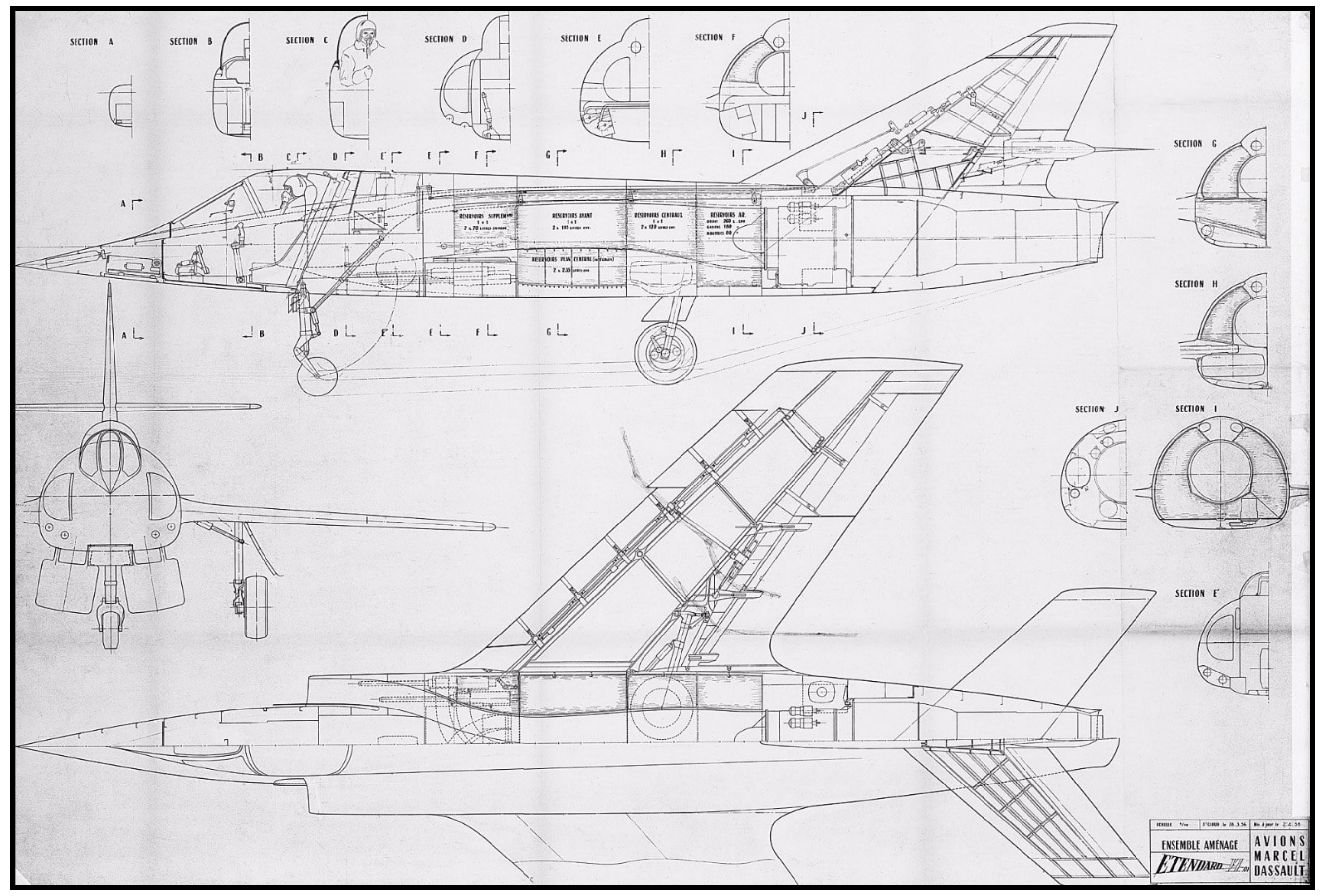

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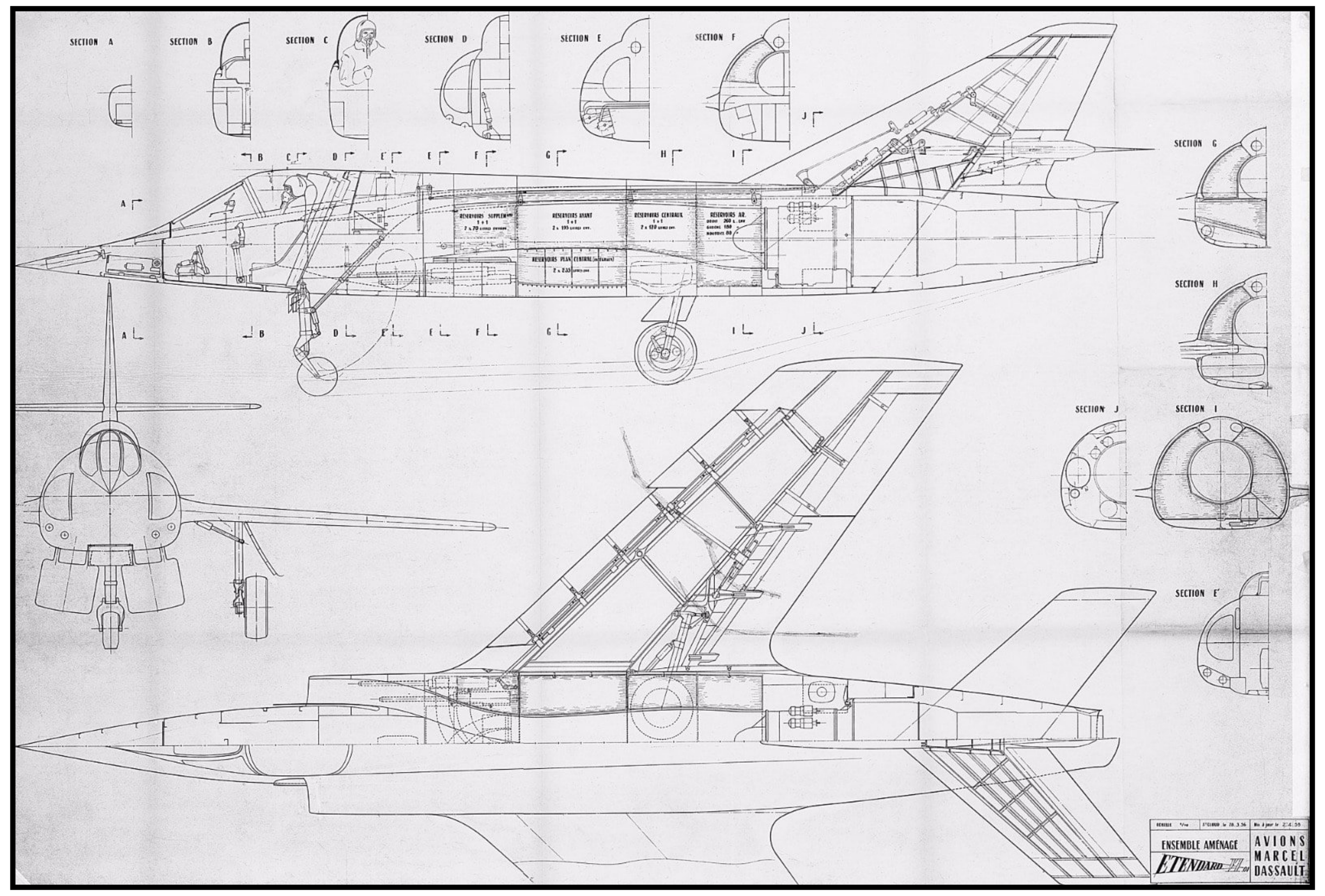

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Answer: Mathematicians

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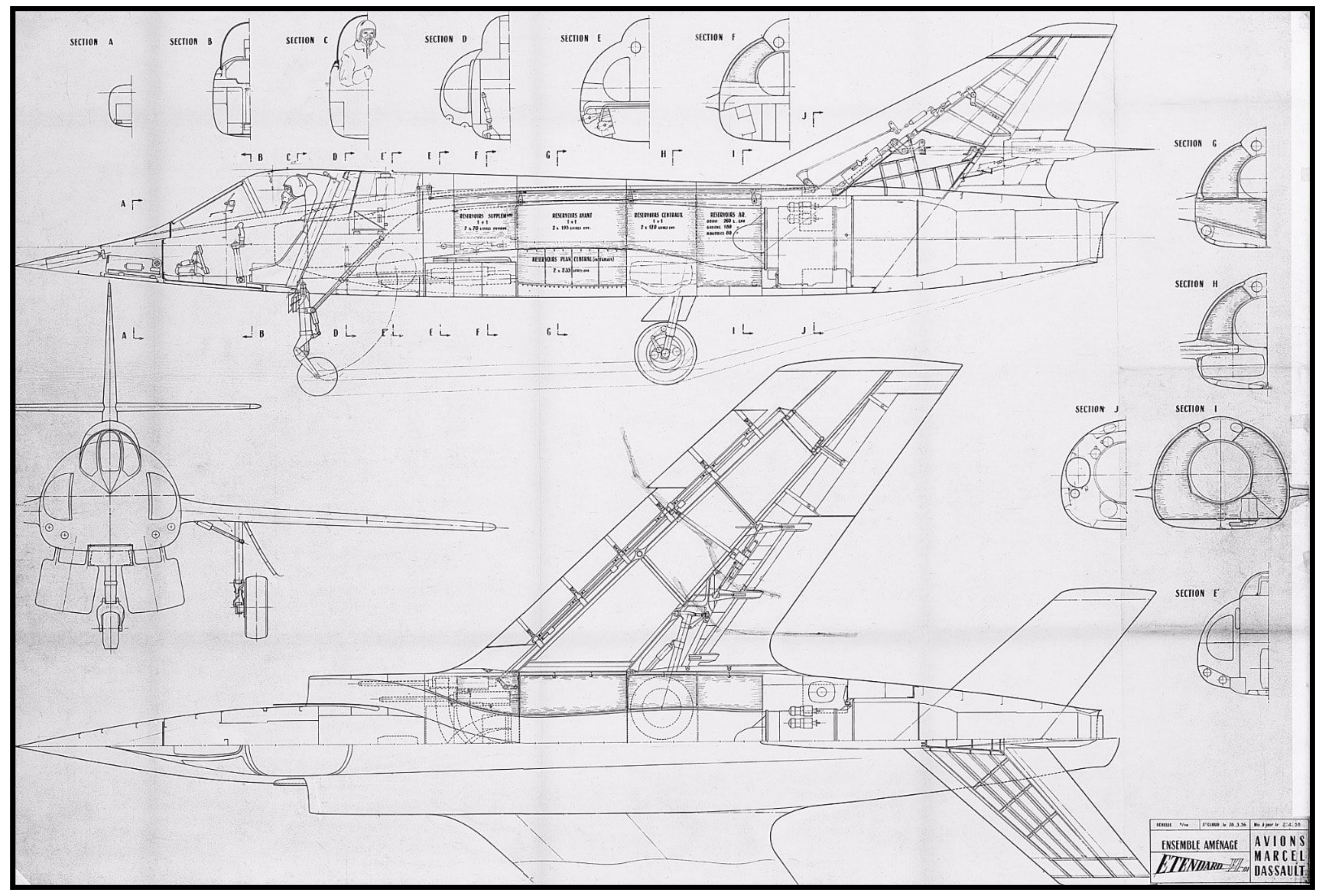

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Answer: **Mathematicians**

(CS320 is a math class, sorry)

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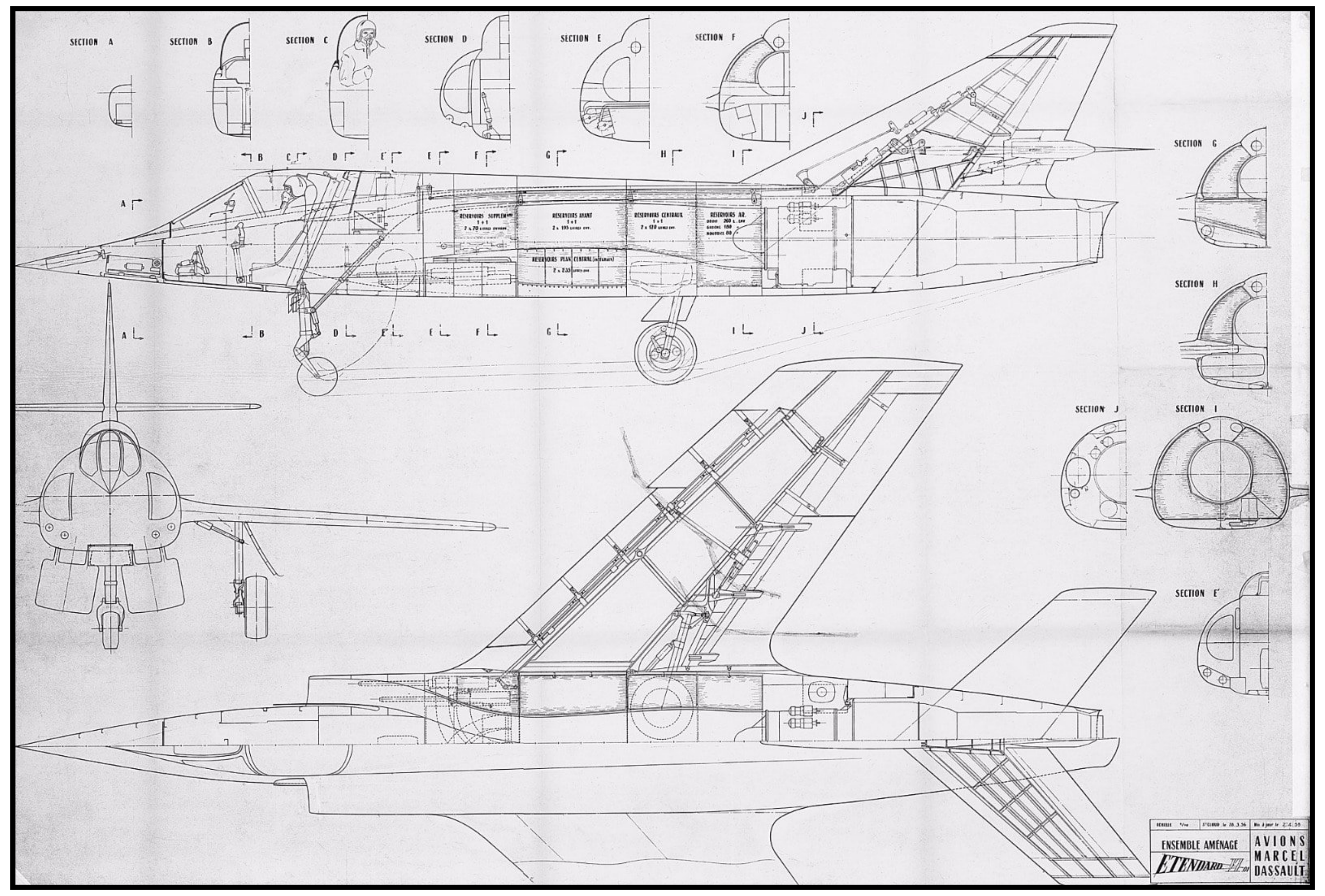

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vs.

Syntax

t	::=		*terms:*
		x	*variable*
		$\lambda\mathsf{x}{:}\mathsf{T}.\mathsf{t}$	*abstraction*
		$\mathsf{t}\ \mathsf{t}$	*application*
v	::=		*values:*
		$\lambda\mathsf{x}{:}\mathsf{T}.\mathsf{t}$	*abstraction value*
T	::=		*types:*
		$\mathsf{T}\to\mathsf{T}$	*type of functions*
Γ	::=		*contexts:*
		$\varnothing$	*empty context*
		$\Gamma, \mathsf{x}{:}\mathsf{T}$	*term variable binding*

Evaluation $\boxed{\mathsf{t} \longrightarrow \mathsf{t}'}$

$$\frac{\mathsf{t}_1 \longrightarrow \mathsf{t}_1'}{\mathsf{t}_1\ \mathsf{t}_2 \longrightarrow \mathsf{t}_1'\ \mathsf{t}_2} \quad \text{(E-APP1)}$$

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$$(\lambda\mathsf{x}{:}\mathsf{T}_{11}.\mathsf{t}_{12})\ \mathsf{v}_2 \longrightarrow [\mathsf{x} \mapsto \mathsf{v}_2]\mathsf{t}_{12} \quad \text{(E-APPABS)}$$

Typing $\boxed{\Gamma \vdash \mathsf{t} : \mathsf{T}}$

$$\frac{\mathsf{x}{:}\mathsf{T} \in \Gamma}{\Gamma \vdash \mathsf{x} : \mathsf{T}} \quad \text{(T-VAR)}$$

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(from T&PL by Pierce)

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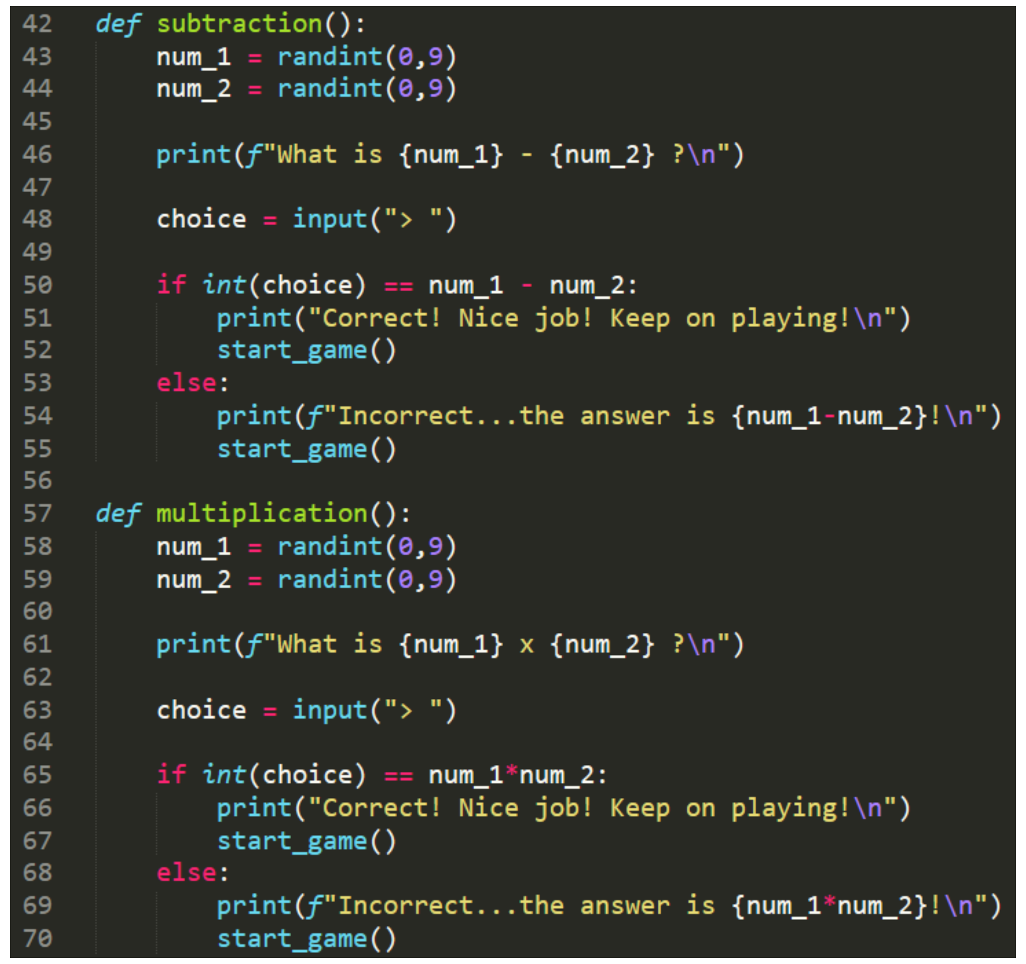
Mathematician's View of PL

» a mathematical object, like a polynomial or a vector

» a formal specification

» composed of exactly three things:

- Syntax
- Type System
- Semantics



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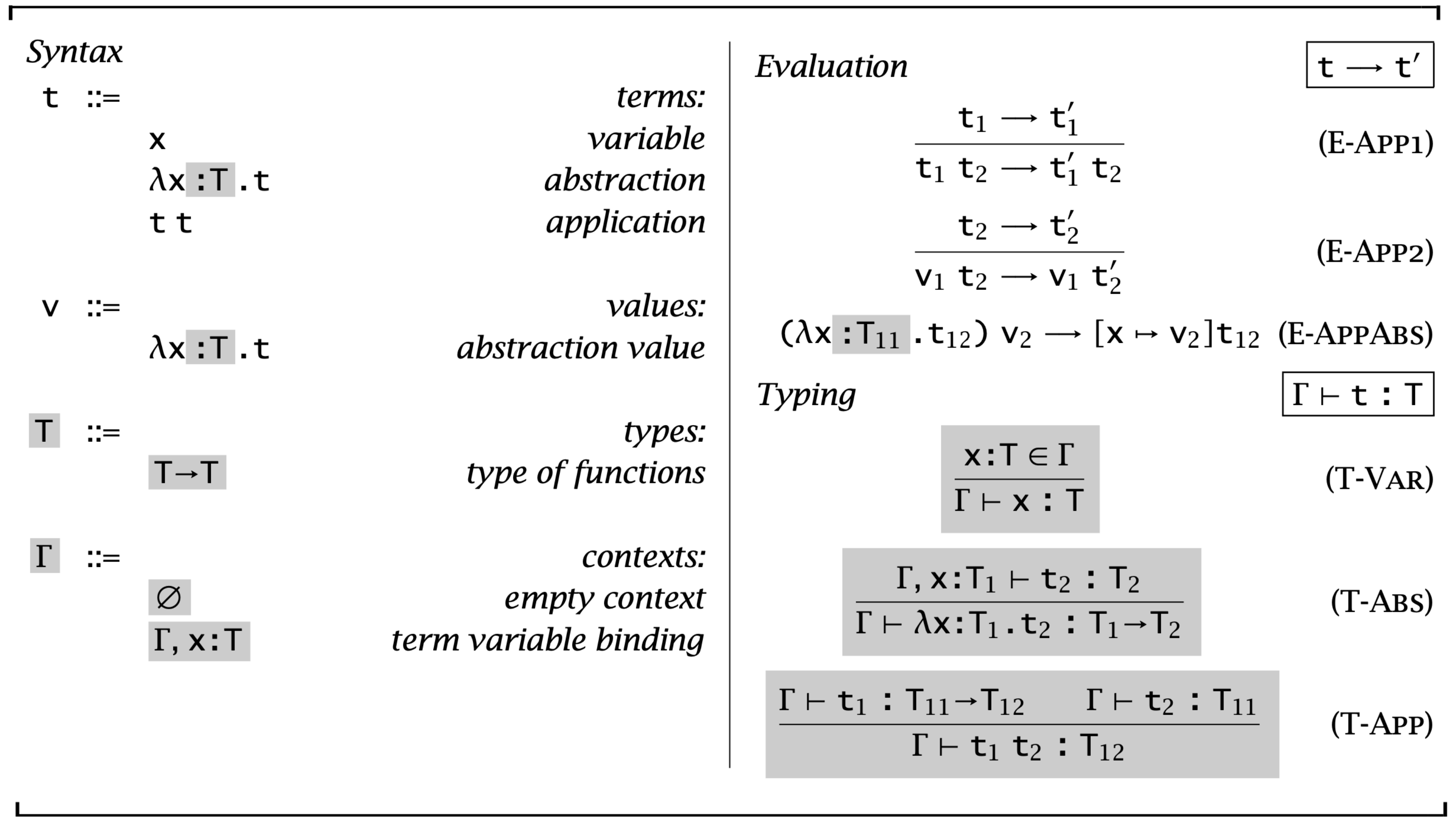

(from T&PL by Pierce)

Why does this matter?

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We want *good* PLs

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This course is about **what makes a PL good**

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This course is about **what makes a PL good**

The punchline: mathematically well-defined syntax, type system, and semantics

Formal PL

The Three Components

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Syntax: What a *well-formed* program in your PL?

```
def f():
    return 3
```

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define f():
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Semantics (Dynamic Semantics): What is the *output* of a (valid) program?

```
>>> 2 + 2
4
```

```
>>> 2 + 2
False
```

For everything we do from now on, we'll define the syntax rules, the typing rules, and the semantic rules

Syntax Rules

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A syntax rule of the form:

*If **<such-and-such>** is a well-formed expression and **<some-other-things>** are a well-formed expression, then **<some-combination-of-such-and-such-and-some-other-things>** is a well-formed expression*

Example: Integer Addition Syntax

If e_1 *is a well-formed expression and* e_2 *is a well-formed expression, then* $e_1 + e_2$ *is a well-formed expression*

2 + (4-3)

Formal notation:

<expr> ::= <expr> + <expr>

Typing Rules

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They are of the form:

*If **<such-and-such>** is of **<such-and-such-type>** and **<some-other-things>** are of **<some-other-types>**, then **<some-combination-of-such-and-such-and-some-other-things>** is of **<some-different-type>***

Example: Integer Addition Typing

If e_1 is an int (in any context Γ) and e_2 is an int then (in any context Γ) $e_1 + e_2$ is an int (in any context Γ)

$$\frac{\emptyset \vdash 2 : \text{int} \qquad \emptyset \vdash (4-3) : \text{int}}{\emptyset \vdash 2 + (4-3) : \text{int}}$$

Formal notation:

$$\frac{\Gamma \vdash e_1 : \texttt{int} \qquad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash e_1 + e_2 : \texttt{int}} \text{(addInt)}$$

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They are of the form:

If **<such-and-such>** evaluates to **<such-and-such-value>** and **<some-other-things>** evaluate to **<some-other-values>** then **<some-combination-of-such-and-such-and-some-other-things>** evaluates to **<some-other-value-computed-based-on-such-and-such-value-and-some-other-values>**

Example: Integer Addition Semantics

If e_1 *evaluates to* v_1 *and* e_2 *evaluates to* v_2*, then* $e_1 + e_2$ *evaluates to* $v_1 + v_2$

Formal Notation:

$$\frac{e_1 \Downarrow v_1 \qquad e_2 \Downarrow v_2}{e_1 + e_2 \Downarrow v_1 + v_2} \text{ (evalInt)}$$

We'll come back to all this soon...

OCaml: A First Look

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- It was developed at Inria (smart researchers in France) in the 90s
- It won the ACM SIGPLAN Programming Languages Software Award in 2023
- It's used/developed heavily by Jane Street (and too a lesser degree by facebook, Microsoft, docker, Wolfram)

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What is OCaml?

OCaml

- **Minimal:** The language is simple, there's very little to it

- **Functional:** A completely different paradigm. We're not writing procedures via commands/statements, we're defining values via expressions

Functional vs. Imperative

Functional here means:

- No state (which means no loops!)
- We don't think of a program as describing a procedure, but as defining a value

State

```python
def fact(n):
    acc = 1
    for i in range(1, n + 1):
        acc *= i # acc is "stateful"
    return acc
```

In Python, we can define variables that change throughout the evaluation of the program

We can't do this in OCaml. Instead we use **recursion**(!)

If you can write recursive functions in Python, then you can program in OCaml

Working with OCaml

Dune

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`Dune is a build tool for OCaml`

Dune

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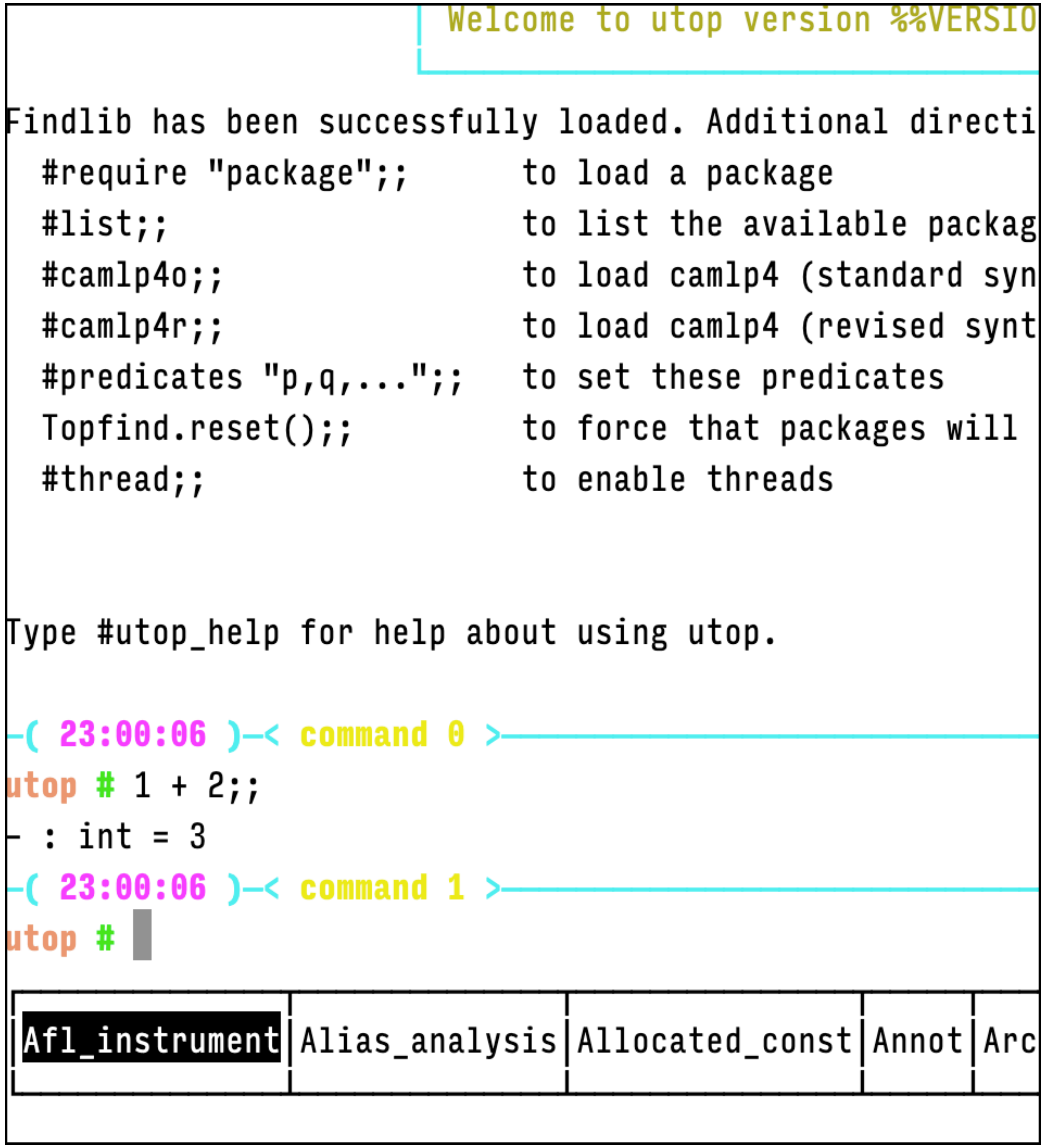
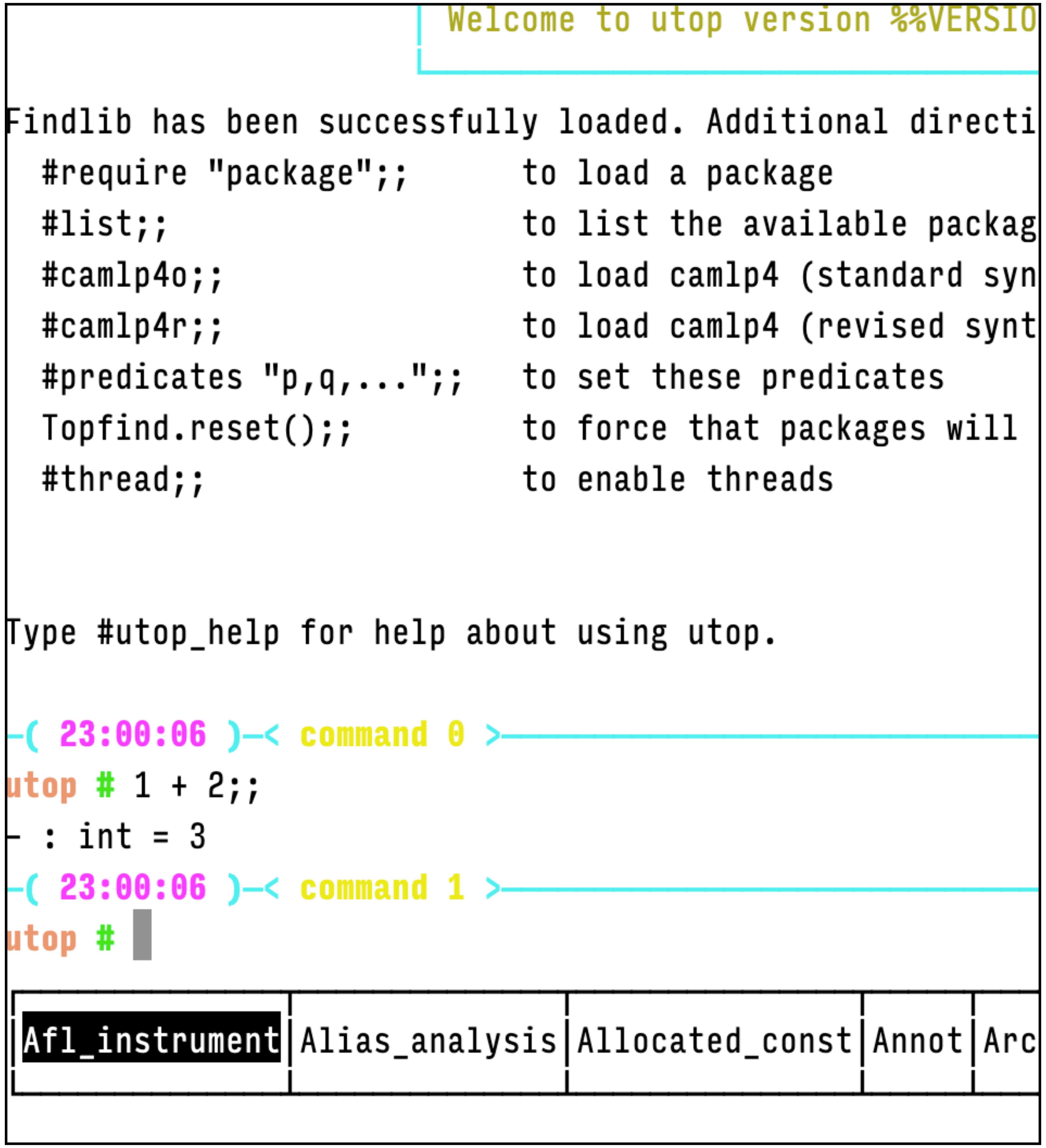
- **dune clean:** removes files created by dune build (not so important but may come in handy)

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



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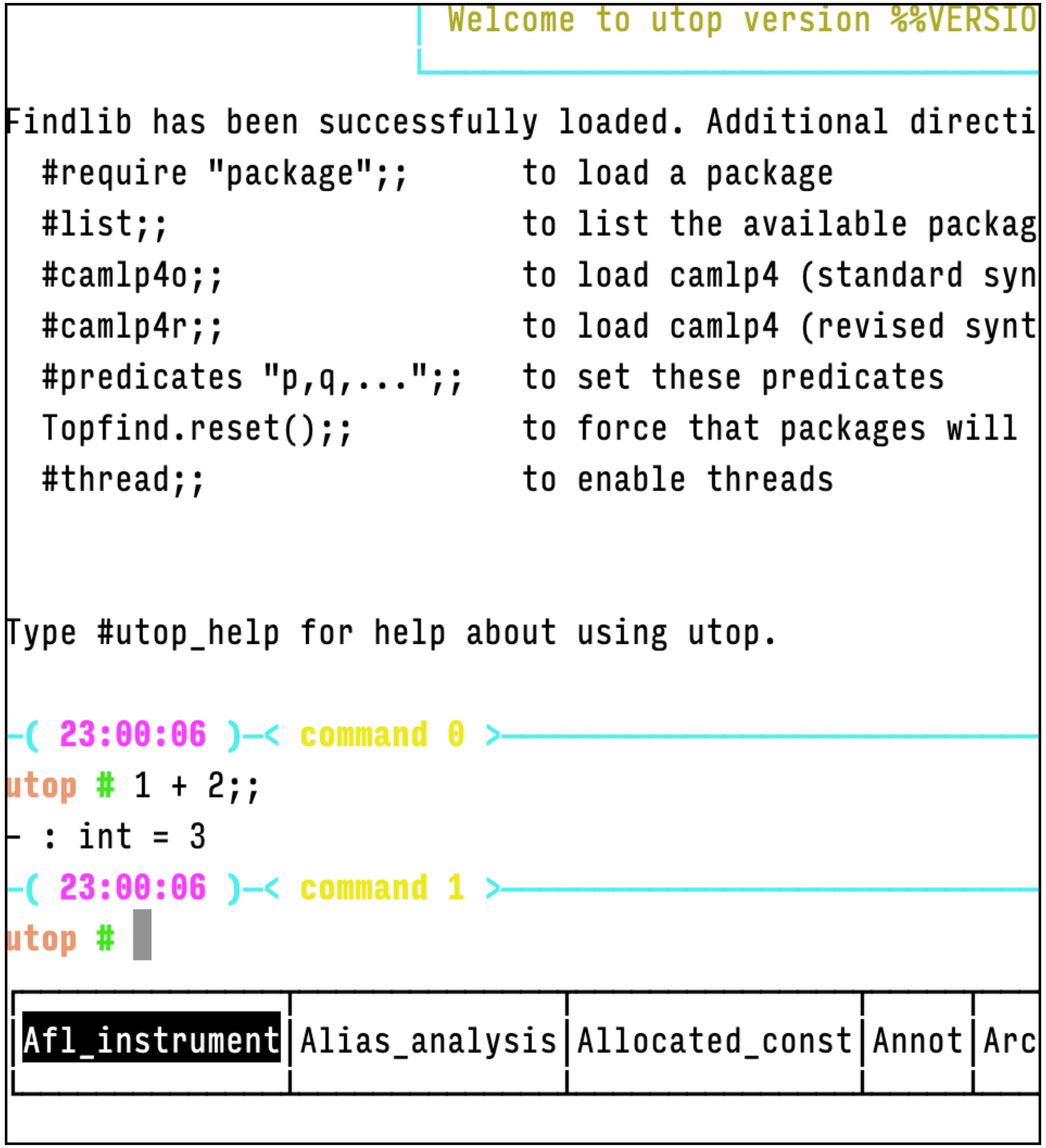

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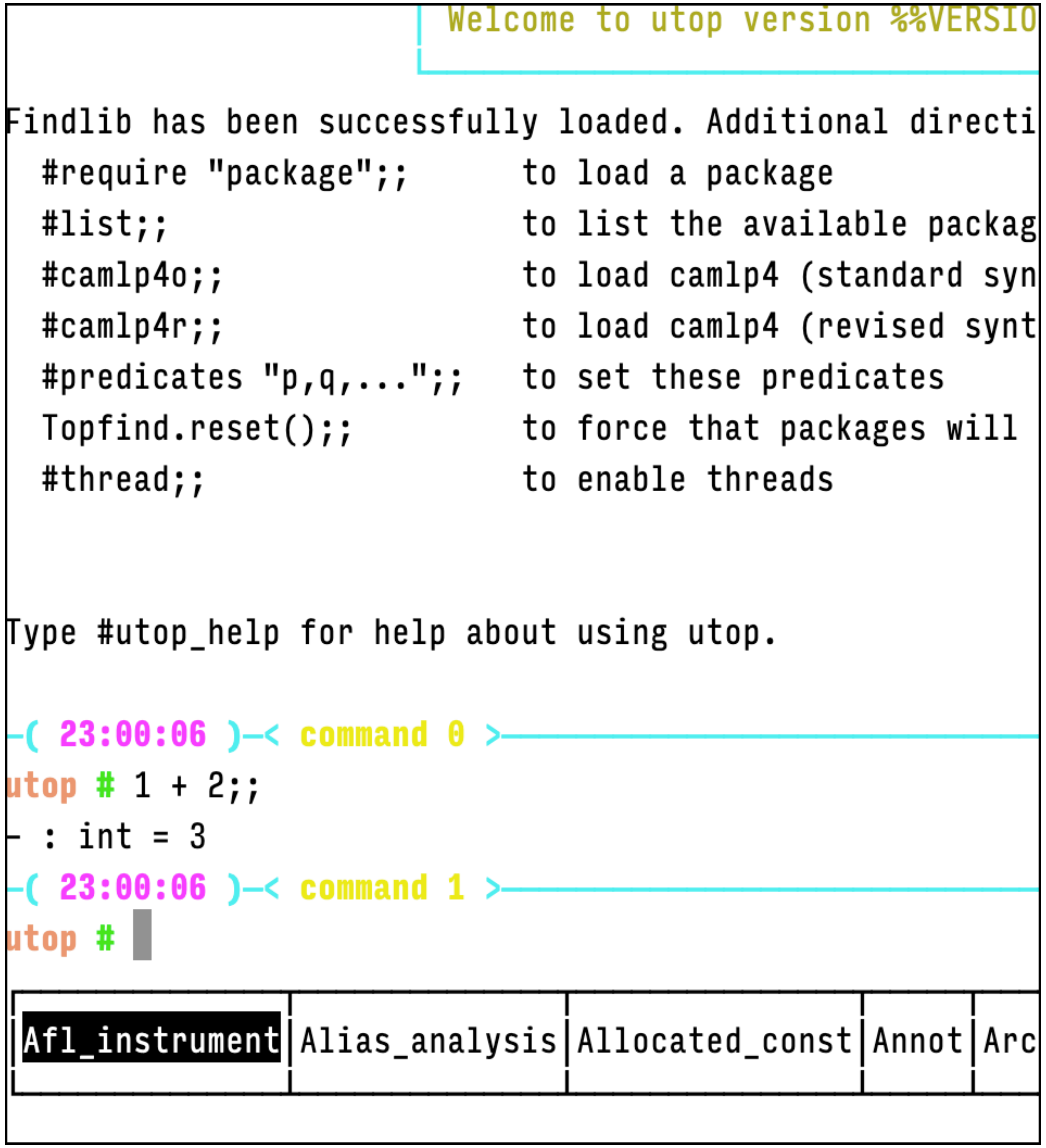

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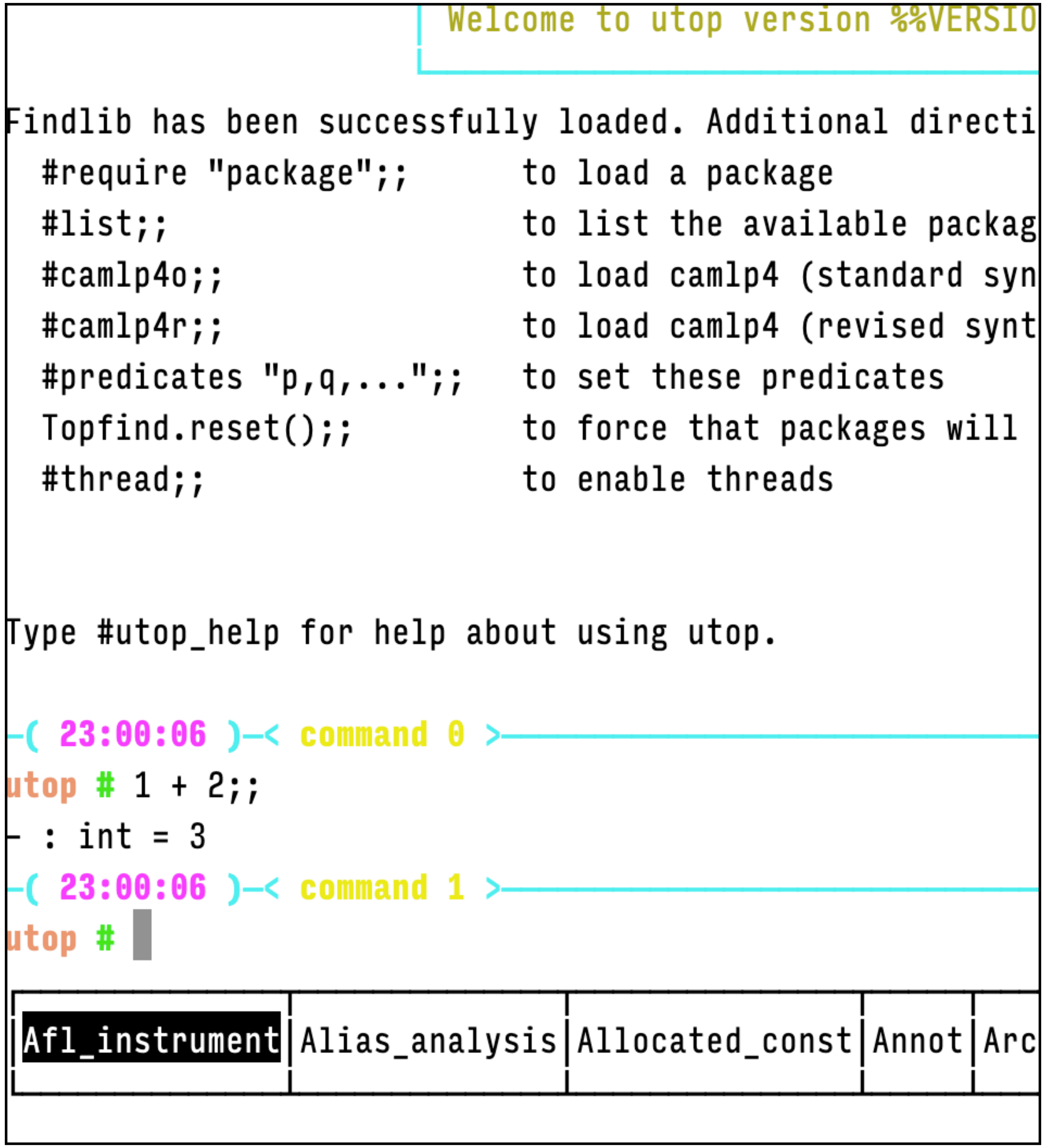

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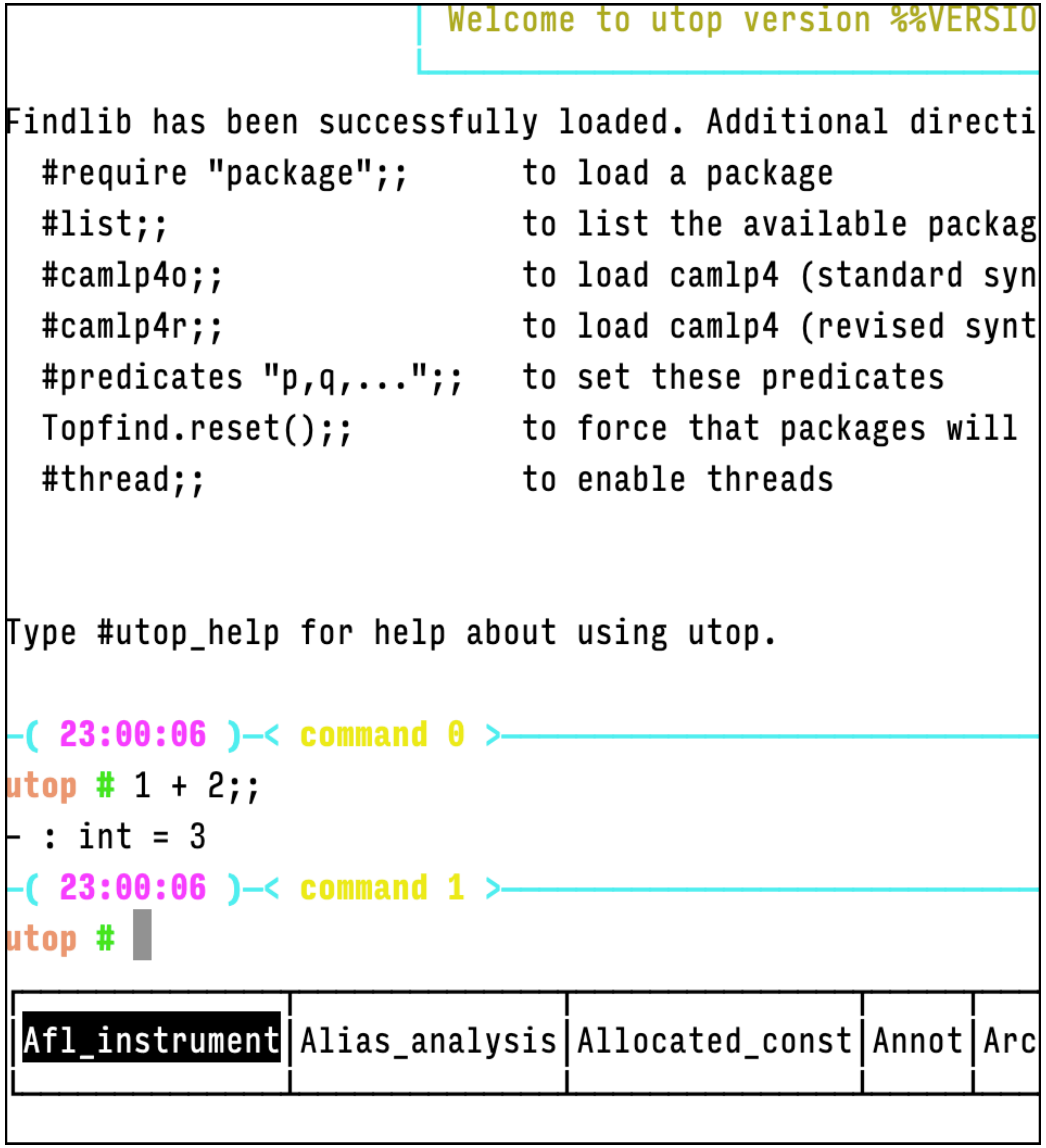
Cheatsheet:

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



A Note on Testing

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then it will be evaluated when you run **dune test** in the project directory

We'll see how to do this much better later on...

The Basics

Anatomy of an OCaml Program

name, not global var.

expression

```
let x = 3

let y = "string"

(* function definition *)
let square x = x * x

(* recursive function definition *)
let rec f x = if x = 0 then 0 else x + f (x - 1)

(* We can't just print , we assign to wildcard *)
let _ = print_endline("Hello world")
```

An OCaml Program consists of *top-level let-expressions*

Expressions

Expressions are <u>syntactic</u> objects which describe values in a program

Mneumonic: ***E****xpressions are* ***EV****aluated to* ***V****alues*

They appear in both functional and imperative PLs, but in functional PLs we *only* have expressions

$$2 + (2 * 3)$$

```
if x = 3 then 3 else 4
```

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

Values

<u>Values</u> are the *things* manipulated and output by programs, e.g., the integer 7 or the string `"seven"`

<u>Expressions</u> *describe* values (the values to which they evaluate

Example: The expression `2 + 7` "describes" the value 9

Types

```
let x : int = 2
let y : string = "two"
let _ = x + y (* THIS IS NOT POSSIBLE *)
```

```
3 | let _ = x + y (* THIS IS NOT POSSIBLE *)
                ^
Error: This expression has type string but an expression was expected of type
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Every expression in OCaml has a <u>type</u>

The type of an expression describes what *kind* of thing it is

Types restrict how expressions can be constructed

Basic Expressions

- Literals
- Let-expressions (local variables)
- If-expressions
- Functions
- Applications

Basic Expressions

- » **Literals**
- » Let-expressions (local variables)
- » If-expressions
- » Functions
- » Applications

Primitive Types and Literals

OCaml has a collection of standard literals and types

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

A Couple Note on Operators

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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 `!=`)

Basic Expressions

» Literals

» **Let-expressions (local variables)**

» If-expressions

» Functions

» Applications

Local Variables

body

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

Local Variables

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

We can define local variables in OCaml

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Local Variables

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

Multiple Local Variables

```python
def sum_of_squares(x, y):
  x_squared = x * x
  y_squared = y * y
  return x_squared + y_squared
```

Python

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

OCaml

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OCaml

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

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OCaml

body

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

Local Variables (Informal)

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let x = 2 in x + x
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syntax: `let VARIABLE = EXPRESSION in BODY`

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body

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let x = 2 in x + x
```

syntax: let VARIABLE = EXPRESSION in BODY

typing: the type is the same as that of BODY *given BODY is well-typed after substituting the VARIABLE in BODY*

semantics: the is the same as the value of BODY *after substituting the VARIABLE in BODY*

Example: Ill-Typed Let-Expression

```
let x = 2 in "two" <> 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*

A Note on Substitution

$$\boxed{\texttt{let x = 2 in x + x}} \longrightarrow \boxed{\texttt{2 + 2}}$$

A Note on Substitution

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

$\longrightarrow$

```
2 + 2
```

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

A Note on Substitution

`let x = 2 in x + x` ⟶ `2 + 2`

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**

A Note on Substitution

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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**

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

A Note on Type Annotations

```
let rec fact (n : int) : int =
  if n <= 0
  then 1
  else n * fact (n - 1)
```

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

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let rec fact (n : int) : int =
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  then 1
  else n * fact (n - 1)
```

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*

Basic Expressions

- Literals
- Let-expressions (local variables)
- **If-expressions**
- Functions
- Applications

If-Expressions

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

Note: OCaml is whitespace agnostic!

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OCaml has expressions for conditional reasoning

If-Expressions

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```

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OCaml has expressions for conditional reasoning

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

If-Expressions

```
let foo x =
  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)

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

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Syntax: if CONDITION then TRUE–CASE else FALSE–CASE

Typing: CONDITION must be a Boolean and TRUE–CASE and FALSE–CASE must be the same type. The type is then the same as that of TRUE–CASE and FALSE–CASE

Semantics: If CONDITION holds, then we get the TRUE–CASE, otherwise we get the FALSE–CASE

Basic Expressions

- Literals
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- **Functions**
- Applications

Functions (Informal)

body

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

Syntax: fun VAR–NAME –> EXPR

Typing: the type of a function is **T1 –> T2** where T1 is the type of the input and T2 is the type of the output

Semantics: A function will evaluate to special ***function value*** (printed as <fun> by utop)

Important: Curried Functions

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

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

Important: Curried 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

Basic Expressions

» Literals

» Let-expressions (local variables)

» If-expressions

» Functions

» **Applications**

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
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Application (Informally)

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Syntax: `FUNCTION–EXPR ARG–EXPR`

Application (Informally)

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Syntax: FUNCTION–EXPR ARG–EXPR

Typing: If FUNCTION–EXPR is of type T1 –> T2, and ARG–EXPR is of type T1, then the type is T2

Application (Informally)

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

Syntax: FUNCTION–EXPR ARG–EXPR

Typing: If FUNCTION–EXPR is of type T1 –> T2, and ARG–EXPR is of type T1, then the type is T2

Semantics: Substitute the value of ARG–EXPR into the body of FUNCTION–EXPR and evaluate that

Application (Example)

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```
(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
```

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

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((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
```

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

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          (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
```

One Last Point: Building Interpreters

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PL is math but we still like to *use* PLs. The three components of a PL correspond to the three things we need to *implement* in an **interpreter** of a PL.

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```
parse : string -> expr
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```
parse : string -> expr
```

» **Type system** is implemented by a **type checker**

```
type_check : expr -> bool (* valid or not *)
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» **Syntax** is implemented by a **parser**

```
parse : string -> expr
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» **Type system** is implemented by a **type checker**

```
type_check : expr -> bool (* valid or not *)
```

» **(Dynamic) semantics** is implemented by an **evaluator**

```
eval : expr -> value
```

Next Steps

- » Make sure you're on Piazza and Gradescope, keep an eye on announcements
- » Bookmark the course webpage and course repo
- » Install opam, VSCode, the course standard library, etc. *(see assignment 1)*
- » **Do the reading listed on the course webpage**

Summary

A PL is a mathematical object given by its **syntax**, **type system** and **semantics**

There is **no state** in functional programming. Programs define the output for a given input

Practice, practice, practice. Functional programming takes time to learn, but once you get it, it's as easy as programming in any other PL