End-to-end language composition

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Our problem

Our problem

We want **better** programming languages

Our problem

We want **better** programming languages

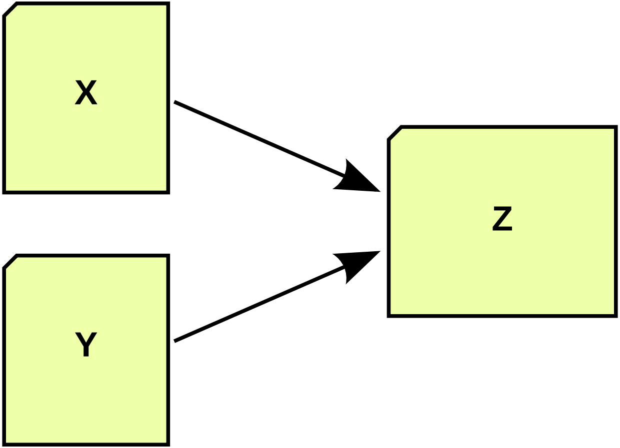
But better always seems to end up **bigger**

Language composition

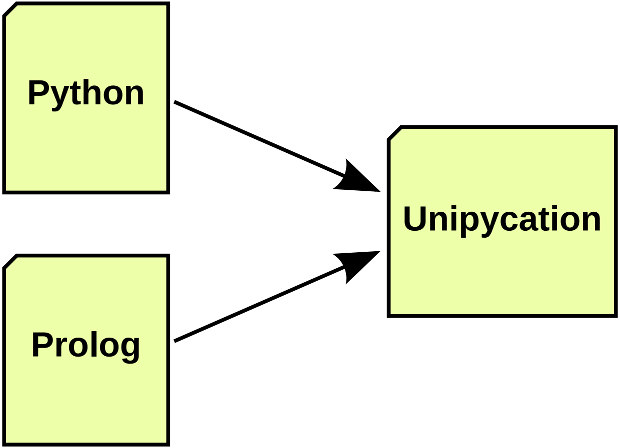
$$\triangleq$$

mixing languages together

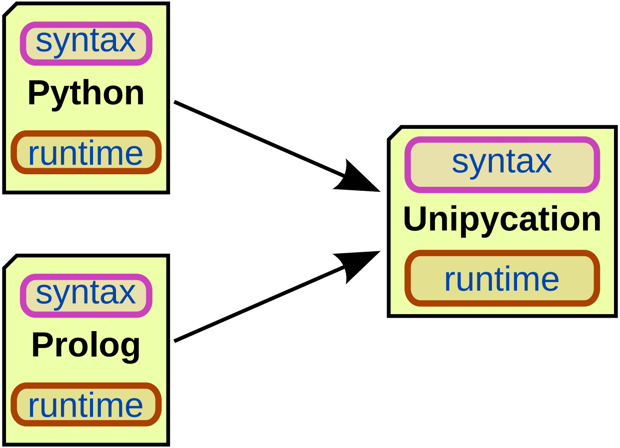
Underlying language composition challenges



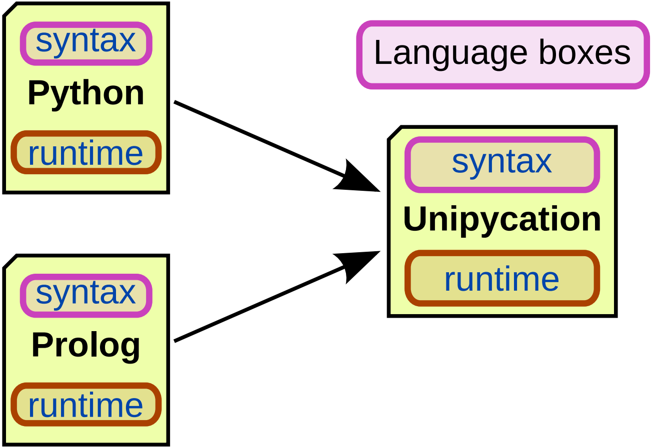
Underlying language composition challenges



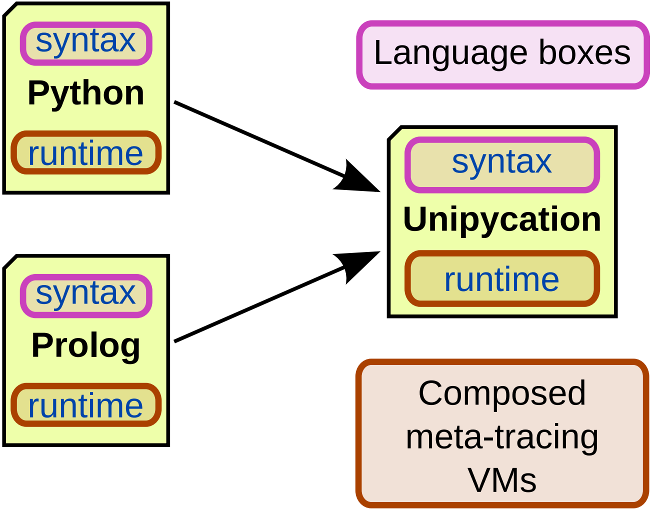
Underlying language composition challenges



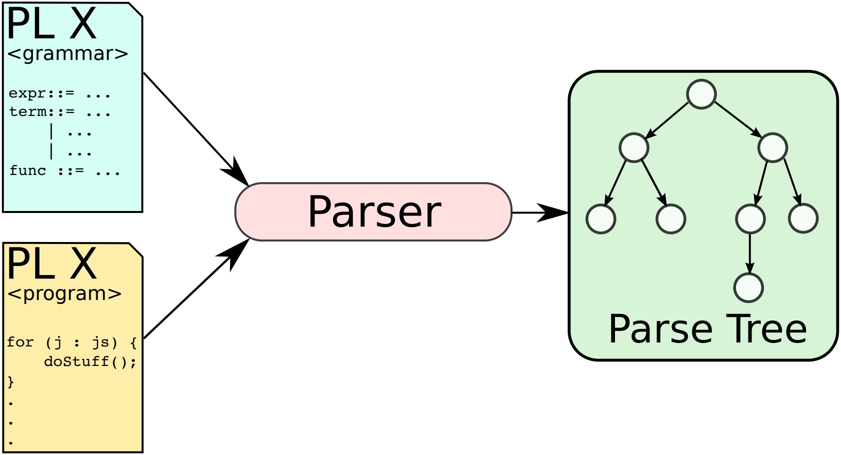
Underlying language composition challenges



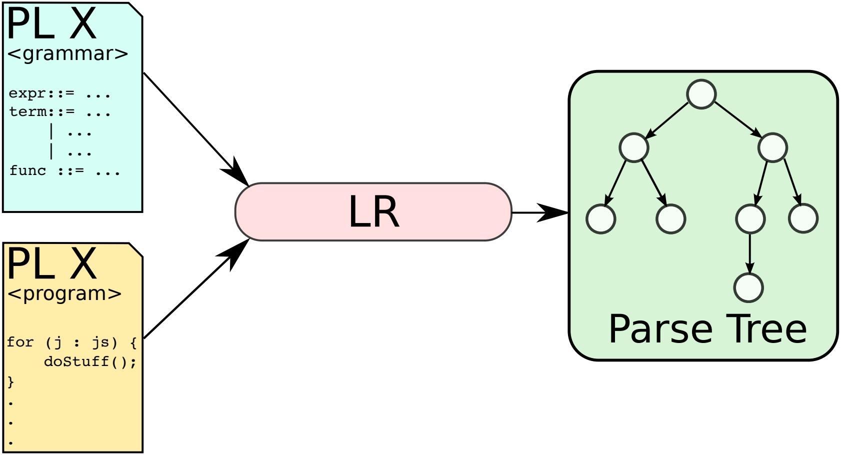
Underlying language composition challenges



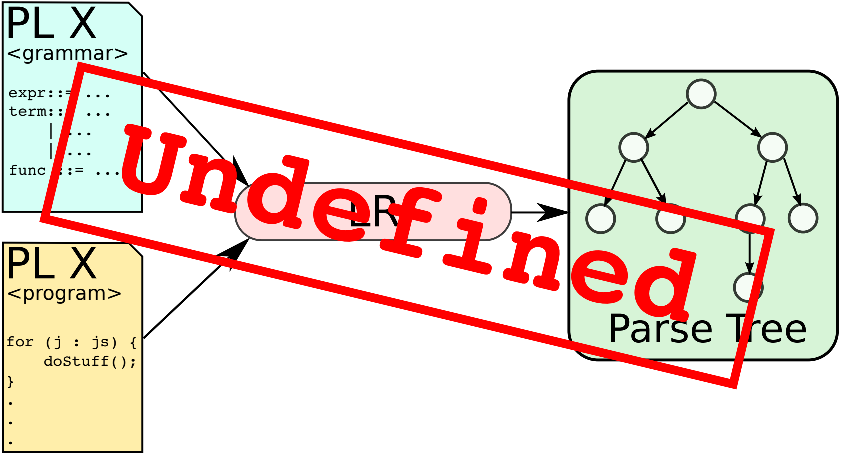
Parsing composition



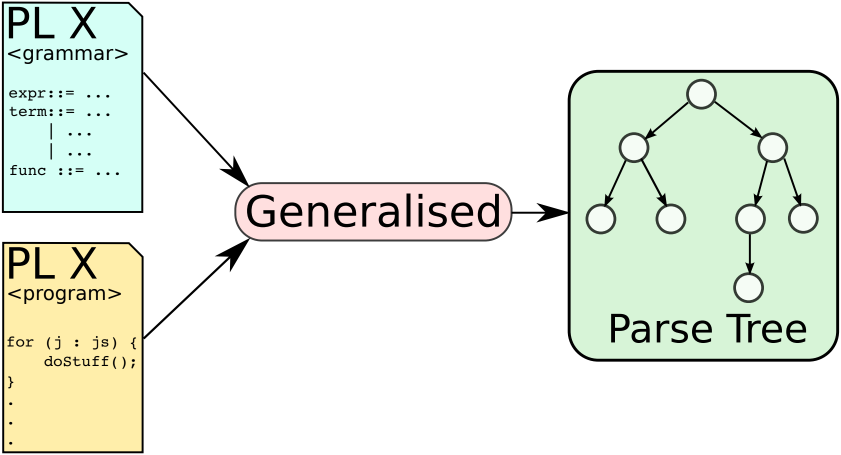
Parsing composition



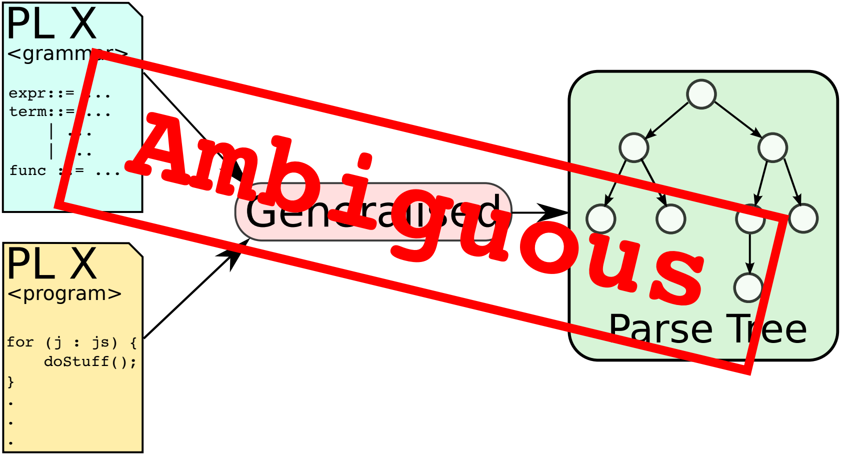
Parsing composition



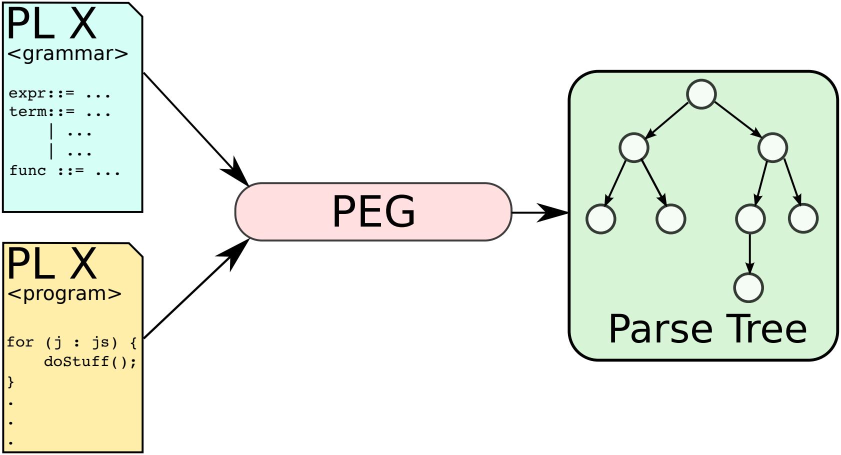
Parsing composition



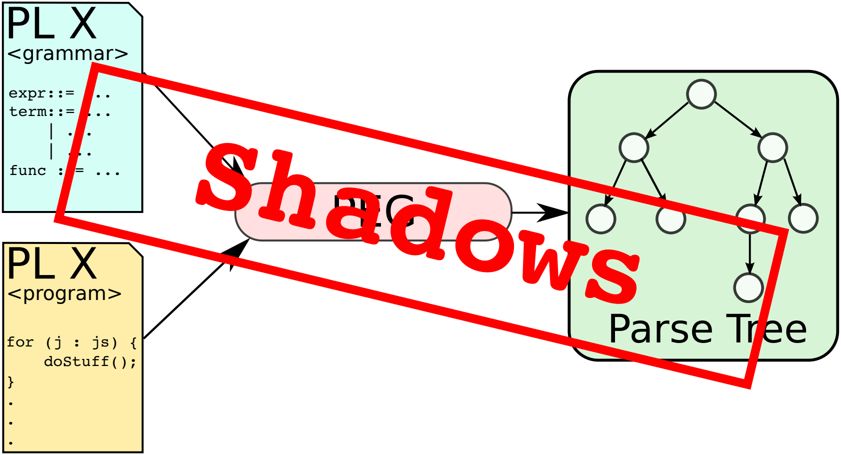
Parsing composition



Parsing composition



Parsing composition



The only choice?

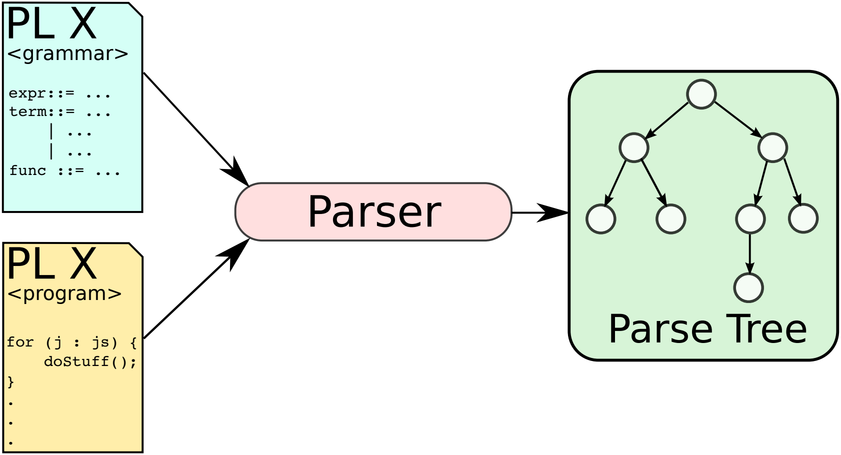
The only choice?

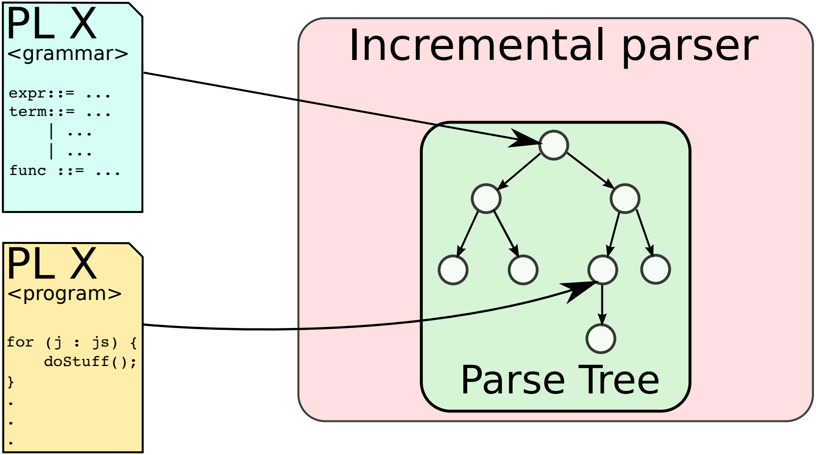
SDE

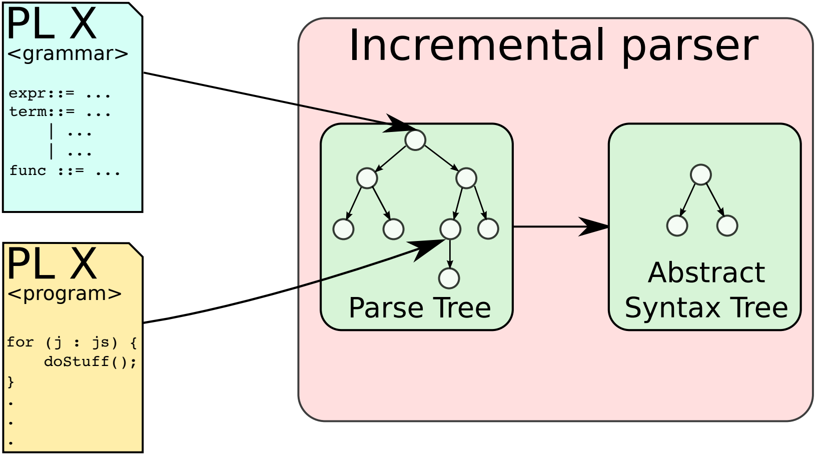
Challenge:
SDE's power $+$
a text editor feel?

Eco demo

Eco

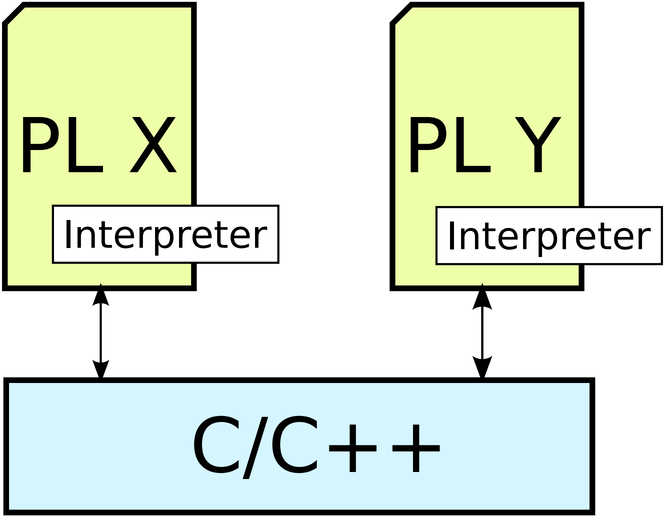

PL X
<grammar>
expr::= ...
term::= ...
| ...
| ...
func ::= ...
PL X
<program>
for (j : js) {
doStuff();
}
.
.
.
Parser
Parse Tree


PL X
<grammar>
expr::= ...
term::= ...
| ...
| ...
func ::= ...
PL X
<program>
for (j : js) {
doStuff();
}
.
.
.
Incremental parser
Parse Tree

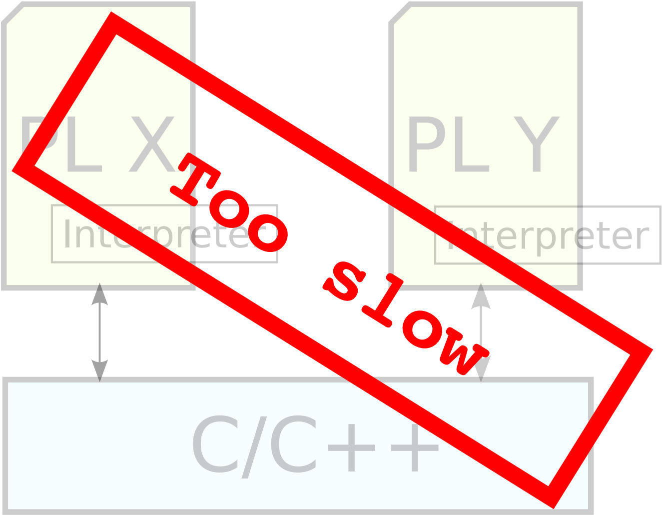

PL X
<grammar>
expr::= ...
term::= ...
| ...
| ...
func ::= ...
PL X
<program>
for (j : js) {
doStuff();
}
.
.
.
Incremental parser
Parse Tree
Abstract
Syntax Tree

Runtime composition

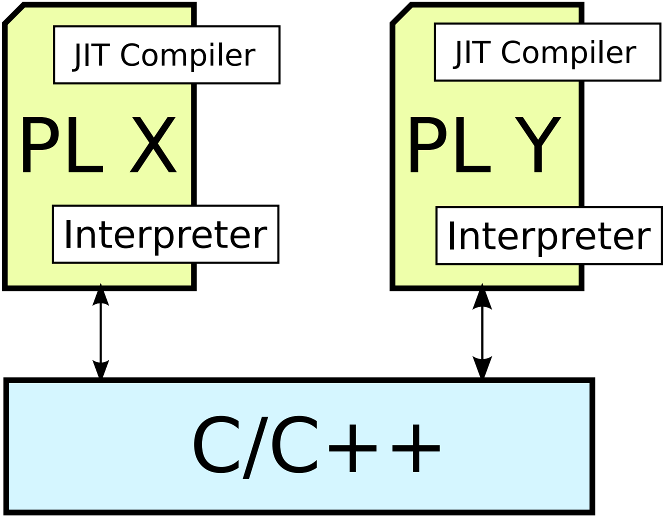
Runtime composition

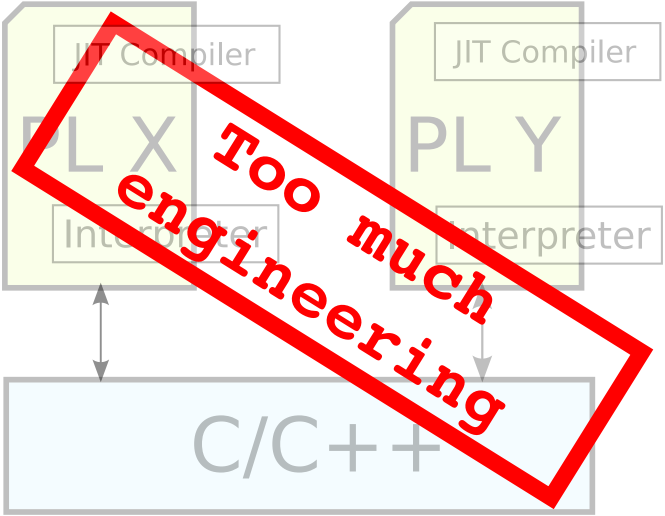


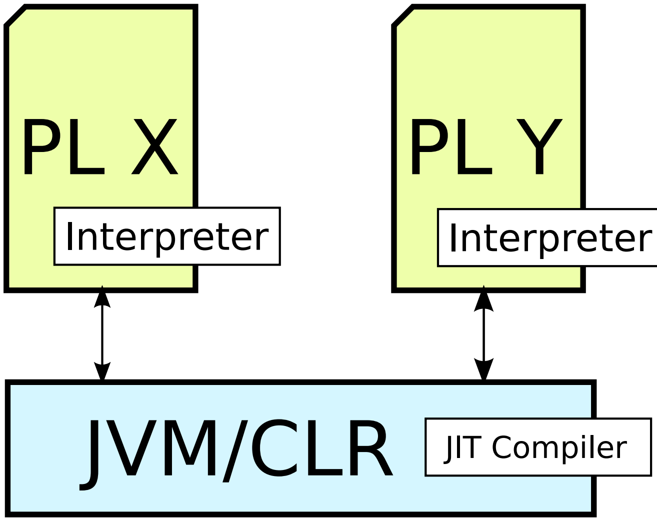
Runtime composition



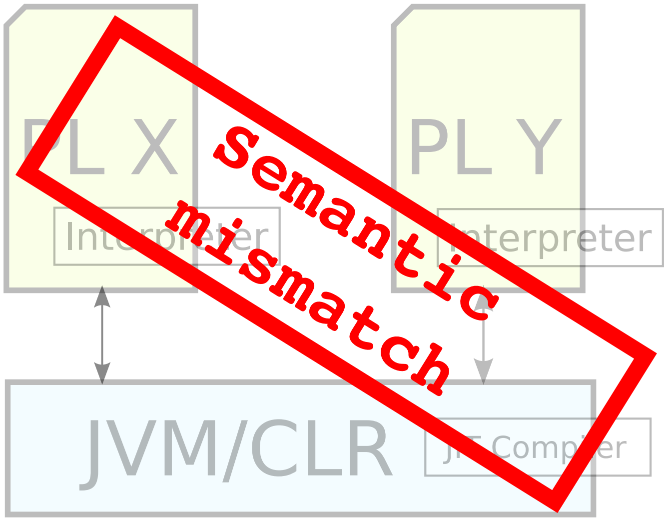
Runtime composition




JIT Compiler
PL X
Interpreter
JIT Compiler
PL Y
Interpreter
C/C++
Too much engineering

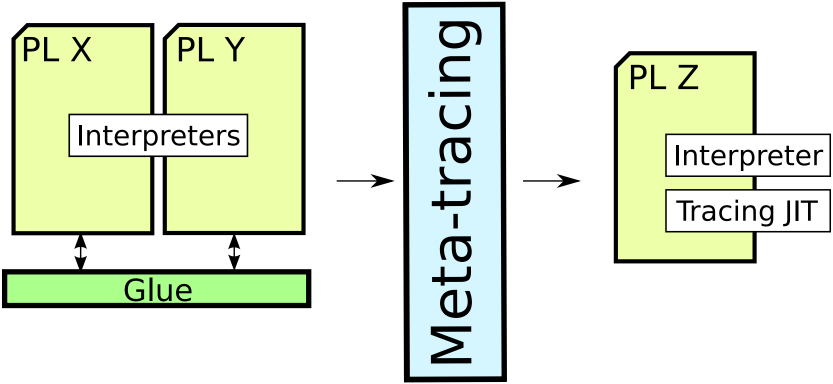

PL X
Interpreter
PL Y
Interpreter
JVM/CLR
JIT Compiler

Runtime composition

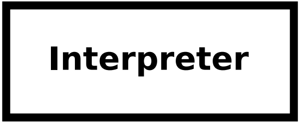


Runtime composition

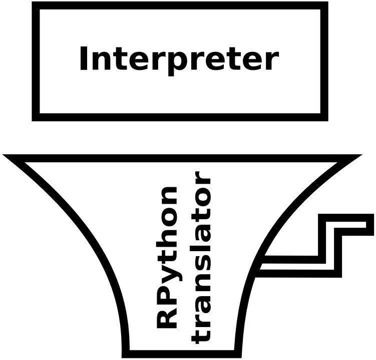
Runtime composition



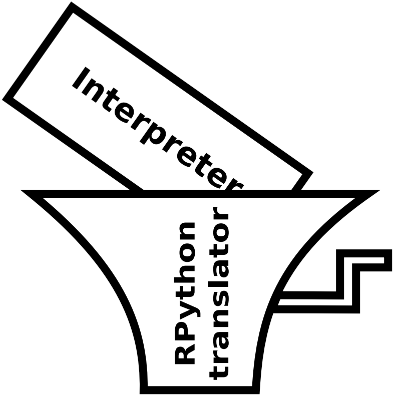
Meta-tracing translation with RPython



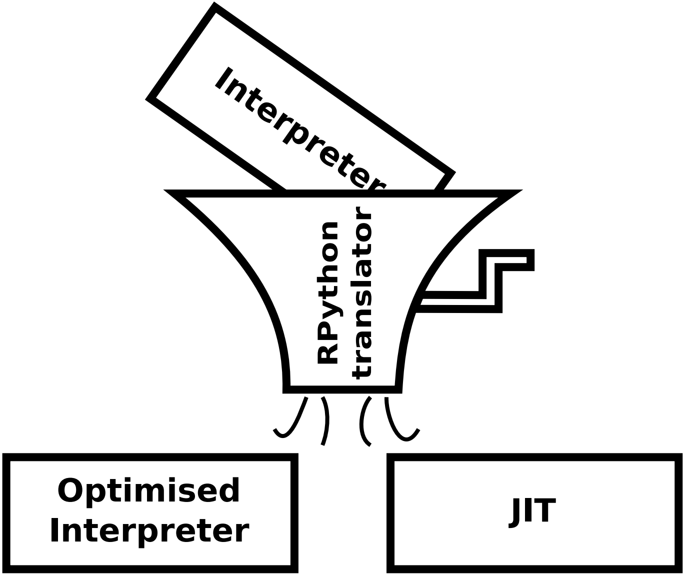
Meta-tracing translation with RPython



Meta-tracing translation with RPython



Meta-tracing translation with RPython



Adding a JIT to an RPython interpreter

```
...
pc := 0
while 1:

    instr := load_next_instruction(pc)
    if instr == POP:
        stack.pop()
        pc += 1
    elif instr == BRANCH:
        off = load_branch_jump(pc)

        pc += off
    elif ...:
        ...
```

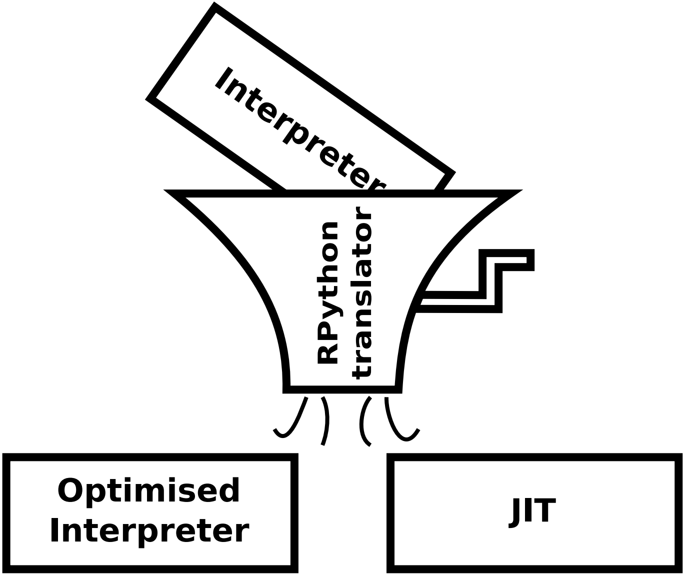
Observation: interpreters are big loops.

Adding a JIT to an RPython interpreter

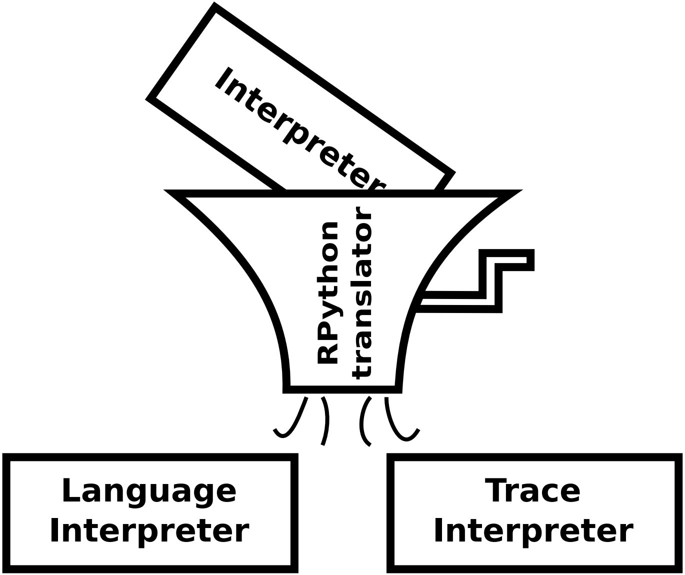
```
...
pc := 0
while 1:
    jit_merge_point(pc)
    instr := load_next_instruction(pc)
    if instr == POP:
        stack.pop()
        pc += 1
    elif instr == BRANCH:
        off = load_branch_jump(pc)
        if off < 0: can_enter_jit(pc)
        pc += off
    elif ...:
        ...
```

Observation: interpreters are big loops.

RPython translation



RPython translation



Tracing JITs

User program (lang *FL*)

```
if x < 0:
  x = x + 1
else:
  x = x + 2
x = x + 3
```

Tracing JITs

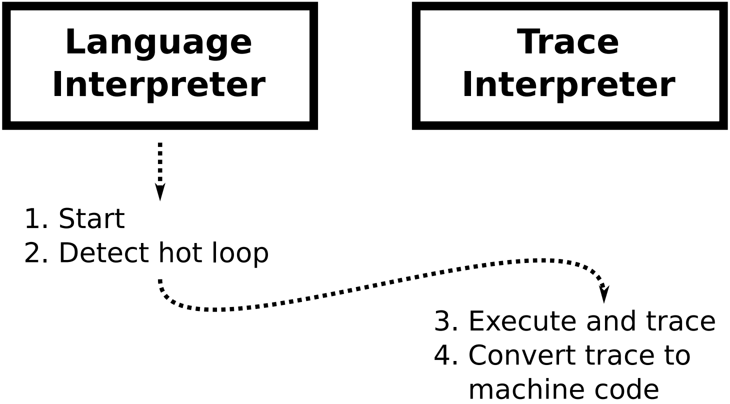
User program (lang *FL*)	Trace when x is set to 6
`if x < 0:`	`guard_type(x, int)`
`  x = x + 1`	`guard_not_less_than(x, 0)`
`else:`	`guard_type(x, int)`
`  x = x + 2`	`x = int_add(x, 2)`
`x = x + 3`	`guard_type(x, int)`
	`x = int_add(x, 3)`

Tracing JITs

User program (lang *FL*)	Optimised trace

`if x < 0:`
`  x = x + 1`
`else:`
`  x = x + 2`
`x = x + 3`
	`guard_type(x, int)`
	`guard_not_less_than(x, 0)`
	`x = int_add(x, 5)`

Meta-tracing VM components



FL Interpreter

```
program_counter = 0; stack = []
vars = {...}
while True:
  jit_merge_point(program_counter)
  instr = load_instruction(program_counter)
  if instr == INSTR_VAR_GET:
    stack.push(
     vars[read_var_name_from_instruction()])
    program_counter += 1
  elif instr == INSTR_VAR_SET:
    vars[read_var_name_from_instruction()]
     = stack.pop()
    program_counter += 1
  elif instr == INSTR_INT:
    stack.push(read_int_from_instruction())
    program_counter += 1
  elif instr == INSTR_LESS_THAN:
    rhs = stack.pop()
    lhs = stack.pop()
    if isinstance(lhs, int) and isinstance(rhs, int):
      if lhs < rhs:
        stack.push(True)
      else:
        stack.push(False)
    else: ...
    program_counter += 1
```

```
elif instr == INSTR_IF:
  result = stack.pop()
  if result == True:
    program_counter += 1
  else:
    program_counter +=
      read_jump_if_instruction()
elif instr == INSTR_ADD:
  lhs = stack.pop()
  rhs = stack.pop()
  if isinstance(lhs, int)
   and isinstance(rhs, int):
    stack.push(lhs + rhs)
  else: ...
  program_counter += 1
```

FL Interpreter

```
program_counter = 0; stack = []
vars = {...}
while True:
  jit_merge_point(program_counter)
  instr = load_instruction(program_counter)
  if instr == INSTR_VAR_GET:
    stack.push(
     vars[read_var_name_from_instruction()])
    program_counter += 1
  elif instr == INSTR_VAR_SET:
    vars[read_var_name_from_instruction()]
     = stack.pop()
    program_counter += 1
  elif instr == INSTR_INT:
    stack.push(read_int_from_instruction())
    program_counter += 1
  elif instr == INSTR_LESS_THAN:
    rhs = stack.pop()
    lhs = stack.pop()
    if isinstance(lhs, int) and isinstance(rhs, int):
      if lhs < rhs:
        stack.push(True)
      else:
        stack.push(False)
    else: ...
    program_counter += 1
```

Meta-tracing JITs

FL Interpreter

```
program_counter = 0; stack = []
vars = {...}
while True:
  jit_merge_point(program_counter)
  instr = load_instruction(program_counter)
  if instr == INSTR_VAR_GET:
    stack.push(
     vars[read_var_name_from_instruction()])
    program_counter += 1
  elif instr == INSTR_VAR_SET:
    vars[read_var_name_from_instruction()]
     = stack.pop()
    program_counter += 1
  elif instr == INSTR_INT:
    stack.push(read_int_from_instruction())
    program_counter += 1
  elif instr == INSTR_LESS_THAN:
    rhs = stack.pop()
    lhs = stack.pop()
    if isinstance(lhs, int) and isinstance(rhs, int):
      if lhs < rhs:
        stack.push(True)
      else:
        stack.push(False)
    else: ...
    program_counter += 1
```

User program (lang *FL*)

```
if x < 0:
  x = x + 1
else:
  x = x + 2
x = x + 3
```

Meta-tracing JITs

FL Interpreter

```
program_counter = 0; stack = []
vars = {...}
while True:
  jit_merge_point(program_counter)
  instr = load_instruction(program_counter)
  if instr == INSTR_VAR_GET:
    stack.push(
     vars[read_var_name_from_instruction()])
    program_counter += 1
  elif instr == INSTR_VAR_SET:
    vars[read_var_name_from_instruction()]
     = stack.pop()
    program_counter += 1
  elif instr == INSTR_INT:
    stack.push(read_int_from_instruction())
    program_counter += 1
  elif instr == INSTR_LESS_THAN:
    rhs = stack.pop()
    lhs = stack.pop()
    if isinstance(lhs, int) and isinstance(rhs, int):
      if lhs < rhs:
        stack.push(True)
      else:
        stack.push(False)
    else: ...
    program_counter += 1
```

Initial trace

```
v0 = <program_counter>
v1 = <stack>
v2 = <vars>
v3 = load_instruction(v0)
guard_eq(v3, INSTR_VAR_GET)
v4 = dict_get(v2, "x")
list_append(v1, v4)
v5 = add(v0, 1)
v6 = load_instruction(v5)
guard_eq(v6, INSTR_INT)
list_append(v1, 0)
v7 = add(v5, 1)
v8 = load_instruction(v7)
guard_eq(v8, INSTR_LESS_THAN)
v9 = list_pop(v1)
v10 = list_pop(v1)
guard_type(v9, int)
guard_type(v10, int)
guard_not_less_than(v9, v10)
list_append(v1, False)
v11 = add(v7, 1)
v12 = load_instruction(v11)
guard_eq(v12, INSTR_IF)
v13 = list_pop(v1)
guard_false(v13)
...
```

Initial trace in full

```
v0 = <program_counter>
v1 = <stack>
v2 = <vars>
v3 = load_instruction(v0)
guard_eq(v3, INSTR_VAR_GET)
v4 = dict_get(v2, "x")
list_append(v1, v4)
v5 = add(v0, 1)
v6 = load_instruction(v5)
guard_eq(v6, INSTR_INT)
list_append(v1, 0)
v7 = add(v5, 1)
v8 = load_instruction(v7)
guard_eq(v8, INSTR_LESS_THAN)
v9 = list_pop(v1)
v10 = list_pop(v1)
guard_type(v9, int)
guard_type(v10, int)
guard_not_less_than(v9, v10)
list_append(v1, False)
v11 = add(v7, 1)
v12 = load_instruction(v11)
guard_eq(v12, INSTR_IF)
v13 = list_pop(v1)
guard_false(v13)
v14 = add(v11, 2)
v15 = load_instruction(v14)
guard_eq(v15, INSTR_VAR_GET)
v16 = dict_get(v2, "x")
list_append(v1, v16)
v17 = add(v14, 1)
v18 = load_instruction(v17)
guard_eq(v18, INSTR_INT)
list_append(v1, 2)
v19 = add(v17, 1)
v20 = load_instruction(v19)
guard_eq(v20, INSTR_ADD)
v21 = list_pop(v1)
v22 = list_pop(v1)
guard_type(v21, int)
guard_type(v22, int)
v23 = add(v22, v21)
list_append(v1, v23)
v24 = add(v19, 1)
v25 = load_instruction(v24)
guard_eq(v25, INSTR_VAR_SET)
v26 = list_pop(v1)
dict_set(v2, "x", v26)
v27 = add(v24, 1)
v28 = load_instruction(v27)
guard_eq(v28, INSTR_VAR_GET)
v29 = dict_get(v2, "x")
list_append(v1, v29)
v30 = add(v27, 1)
v31 = load_instruction(v30)
guard_eq(v31, INSTR_INT)
list_append(v1, 3)
v32 = add(v30, 1)
v33 = load_instruction(v32)
guard_eq(v33, INSTR_ADD)
v34 = list_pop(v1)
v35 = list_pop(v1)
guard_type(v34, int)
guard_type(v35, int)
v36 = add(v35, v34)
list_append(v1, v36)
v37 = add(v32, 1)
v38 = load_instruction(v37)
guard_eq(v38, INSTR_VAR_SET)
v39 = list_pop(v1)
dict_set(v2, "x", v39)
v40 = add(v37, 1)
```

Trace optimisation (1)

Removing constants (from `jit_merge_point`)

```
v1 = <stack>
v2 = <vars>
v4 = dict_get(v2, "x")
list_append(v1, v4)
list_append(v1, 0)
v9 = list_pop(v1)
v10 = list_pop(v1)
guard_type(v9, int)
guard_type(v10, int)
guard_not_less_than(v9, v10)
list_append(v1, False)
v13 = list_pop(v1)
guard_false(v13)
v16 = dict_get(v2, "x")
list_append(v1, v16)
list_append(v1, 2)
v21 = list_pop(v1)
v22 = list_pop(v1)
guard_type(v21, int)
guard_type(v22, int)
v23 = add(v22, v21)
list_append(v1, v23)
v26 = list_pop(v1)
dict_set(v2, "x", v26)
v29 = dict_get(v2, "x")
list_append(v1, v29)
list_append(v1, 3)
v34 = list_pop(v1)
v35 = list_pop(v1)
guard_type(v34, int)
guard_type(v35, int)
v36 = add(v35, v34)
list_append(v1, v36)
v39 = list_pop(v1)
dict_set(v2, "x", v39)
```

Optimisation #2 & #3

List folded trace

```
v1 = <stack>
v2 = <vars>
v4 = dict_get(v2, "x")
guard_type(v4, int)
guard_not_less_than(v4, 0)
v16 = dict_get(v2, "x")
guard_type(v16, int)
v23 = add(v16, 2)
dict_set(v2, "x", v23)
v29 = dict_get(v2, "x")
guard_type(v29, int)
v36 = add(v29, 3)
dict_set(v2, "x", v36)
```

Optimisation #2 & #3

List folded trace	Dict folded trace

`v1 = <stack>`
`v2 = <vars>`
`v4 = dict_get(v2, "x")`
`guard_type(v4, int)`
`guard_not_less_than(v4, 0)`
`v16 = dict_get(v2, "x")`
`guard_type(v16, int)`
`v23 = add(v16, 2)`
`dict_set(v2, "x", v23)`
`v29 = dict_get(v2, "x")`
`guard_type(v29, int)`
`v36 = add(v29, 3)`
`dict_set(v2, "x", v36)`
	`v1 = <stack>`
	`v2 = <vars>`
	`v4 = dict_get(v2, "x")`
	`guard_type(v4, int)`
	`guard_not_less_than(v4, 0)`
	`v23 = add(v4, 2)`
	`guard_type(v23, int)`
	`v36 = add(v23, 3)`
	`dict_set(v2, "x", v36)`

Optimisation #4 & #5

Type folded trace

```
v1 = <stack>
v2 = <vars>
v4 = dict_get(v2, "x")
guard_type(v4, int)
guard_not_less_than(v4, 0)
v23 = add(v4, 2)
v36 = add(v23, 3)
dict_set(v2, "x", v36)
```

Optimisation #4 & #5

Type folded trace	Arithmetic folded trace

`v1 = <stack>`
`v2 = <vars>`
`v4 = dict_get(v2, "x")`
`guard_type(v4, int)`
`guard_not_less_than(v4, 0)`
`v23 = add(v4, 2)`
`v36 = add(v23, 3)`
`dict_set(v2, "x", v36)`
	`v1 = <stack>`
	`v2 = <vars>`
	`v4 = dict_get(v2, "x")`
	`guard_type(v4, int)`
	`guard_not_less_than(v4, 0)`
	`v23 = add(v4, 5)`
	`dict_set(v2, "x", v23)`

Optimisation #4 & #5

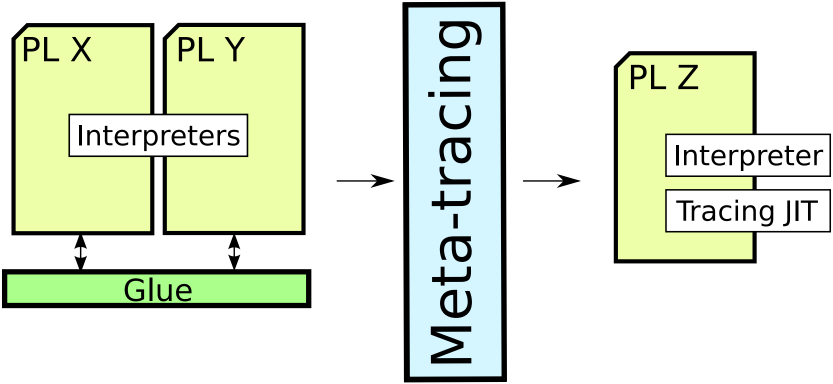
Type folded trace	Arithmetic folded trace

`v1 = <stack>`
`v2 = <vars>`
`v4 = dict_get(v2, "x")`
`guard_type(v4, int)`
`guard_not_less_than(v4, 0)`
`v23 = add(v4, 2)`
`v36 = add(v23, 3)`
`dict_set(v2, "x", v36)`
	`v1 = <stack>`
	`v2 = <vars>`
	`v4 = dict_get(v2, "x")`
	`guard_type(v4, int)`
	`guard_not_less_than(v4, 0)`
	`v23 = add(v4, 5)`
	`dict_set(v2, "x", v23)`

Trace optimisation: from 72 trace elements to 7.

Runtime composition recap

Runtime composition recap



Unipycation demo

Warning: draft numbers ahead

Absolute timing comparison

VM	Benchmark	*Python*		*Prolog*		*Python → Prolog*	
CPython-SWI	SmallFunc	0.125s	±0.006	0.257s	±0.001	28.893s	±0.175
	Loop1Arg0Result	2.924s	±0.215	7.352s	±0.037	9.310s	±0.065
	Loop1Arg1Result	4.184s	±0.028	18.890s	±0.082	20.865s	±0.050
	NondetLoop1Arg1Result	7.531s	±0.065	18.643s	±0.159	667.682s	±5.594
	TermConstruction	264.415s	±1.815	48.819s	±0.208	2185.150s	±14.251
	Lists	9.374s	±0.046	25.148s	±0.182	2207.304s	±12.344
PyPy-SWI	SmallFunc	0.001s	±0.000	0.256s	±0.001	4.744s	±0.062
	Loop1Arg0Result	0.085s	±0.000	7.358s	±0.067	7.583s	±0.103
	Loop1Arg1Result	0.112s	±0.000	18.988s	±0.115	18.519s	±0.111
	NondetLoop1Arg1Result	0.481s	±0.007	18.737s	±0.247	74.833s	±1.856
	TermConstruction	6.111s	±0.029	48.897s	±0.370	166.107s	±3.218
	Lists	1.102s	±0.010	25.104s	±0.189	163.505s	±3.586
Unipycation	SmallFunc	0.001s	±0.000	0.006s	±0.001	0.001s	±0.000
	Loop1Arg0Result	0.085s	±0.000	0.086s	±0.000	0.087s	±0.000
	Loop1Arg1Result	0.112s	±0.000	0.114s	±0.000	0.115s	±0.000
	NondetLoop1Arg1Result	0.500s	±0.002	0.548s	±0.064	2.674s	±0.010
	TermConstruction	6.053s	±0.218	2.444s	±0.002	36.069s	±0.171
	Lists	0.845s	±0.002	1.416s	±0.003	5.056s	±0.026
Jython-tuProlog	SmallFunc	0.088s	±0.002	3.050s	±0.036	52.294s	±0.371
	Loop1Arg0Result	1.078s	±0.007	206.590s	±2.884	199.963s	±1.784
	Loop1Arg1Result	2.145s	±0.175	293.311s	±4.270	294.781s	±4.746
	NondetLoop1Arg1Result	7.939s	±0.341	timeout		timeout	
	TermConstruction	timeout		timeout		timeout	
	Lists	timeout		timeout		timeout	

Relative timing comparison

VM	Benchmark	$\frac{\textit{Python}\rightarrow\textit{Prolog}}{\textit{Python}}$		$\frac{\textit{Python}\rightarrow\textit{Prolog}}{\textit{Prolog}}$		$\frac{\textit{Python}\rightarrow\textit{Prolog}}{\text{Unipycation}}$	
CPython-SWI	SmallFunc	231.770×	±10.154	112.567×	±0.934	27821.079×	±1896.725
	Loop1Arg0Result	3.184×	±0.232	1.266×	±0.011	107.591×	±0.779
	Loop1Arg1Result	4.987×	±0.039	1.105×	±0.006	181.899×	±0.444
	NondetLoop1Arg1Result	88.654×	±1.026	35.814×	±0.389	249.737×	±2.244
	TermConstruction	8.264×	±0.081	44.760×	±0.348	60.583×	±0.487
	Lists	235.459×	±1.742	87.772×	±0.789	436.609×	±3.494
PyPy-SWI	SmallFunc	5747.739×	±101.546	18.515×	±0.254	4568.213×	±304.275
	Loop1Arg0Result	88.765×	±1.271	1.031×	±0.019	87.636×	±1.316
	Loop1Arg1Result	164.697×	±1.127	0.975×	±0.009	161.446×	±1.006
	NondetLoop1Arg1Result	155.478×	±4.537	3.994×	±0.111	27.990×	±0.705
	TermConstruction	27.179×	±0.522	3.397×	±0.068	4.605×	±0.091
	Lists	148.418×	±3.265	6.513×	±0.142	32.342×	±0.703
Unipycation	SmallFunc	1.295×	±0.086	0.182×	±0.036	1.000×	
	Loop1Arg0Result	1.020×	±0.001	1.012×	±0.002	1.000×	
	Loop1Arg1Result	1.025×	±0.002	1.002×	±0.002	1.000×	
	NondetLoop1Arg1Result	5.349×	±0.035	4.879×	±0.631	1.000×	
	TermConstruction	5.959×	±0.224	14.756×	±0.069	1.000×	
	Lists	5.982×	±0.034	3.569×	±0.019	1.000×	
Jython-tuProlog	SmallFunc	592.904×	±14.602	17.143×	±0.259	50354.204×	±3330.993
	Loop1Arg0Result	185.460×	±2.182	0.968×	±0.017	2310.844×	±21.996
	Loop1Arg1Result	137.427×	±11.805	1.005×	±0.022	2569.873×	±41.331
	NondetLoop1Arg1Result	timeout		timeout		timeout	
	TermConstruction	timeout		timeout		timeout	
	Lists	timeout		timeout		timeout	

What can we use this for?

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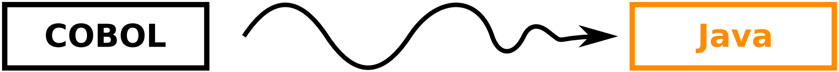
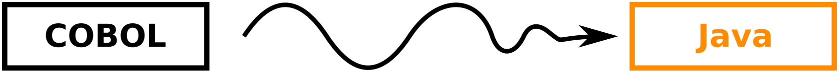
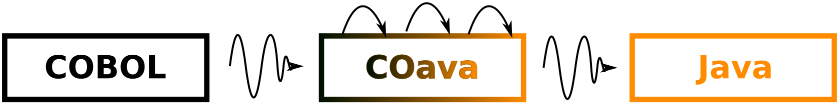


What can we use this for?

"Big Bang" translation

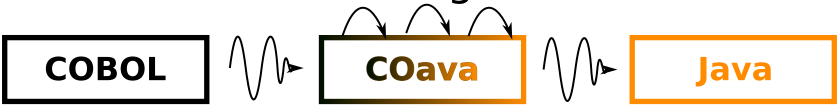


What can we use this for?



What can we use this for?

Gradual migration



What's next?

Editor: incremental semantic analysis on ASTs and code generation

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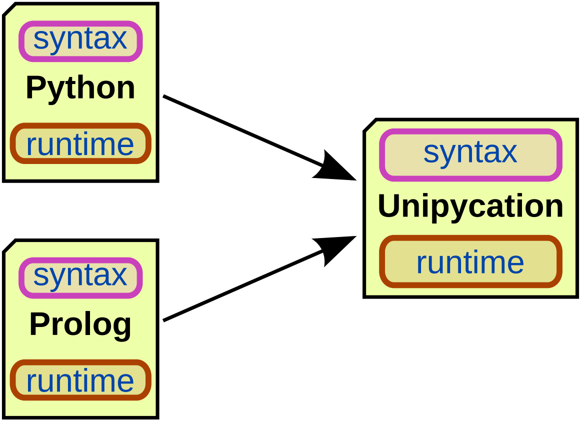
VMs: uncovering common idioms

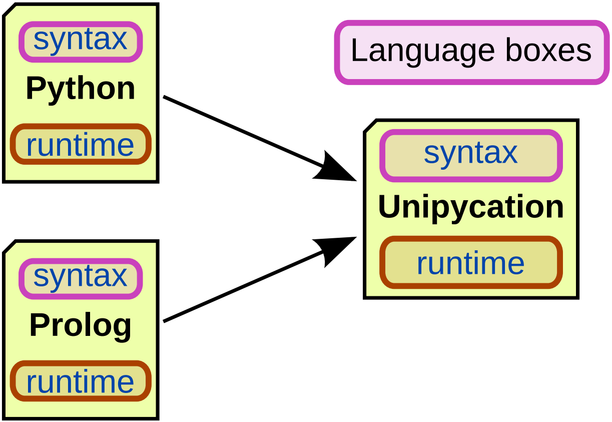
Summary

Summary



syntax
Python
runtime
syntax
Prolog
runtime
syntax
Unipycation
runtime

Summary


syntax
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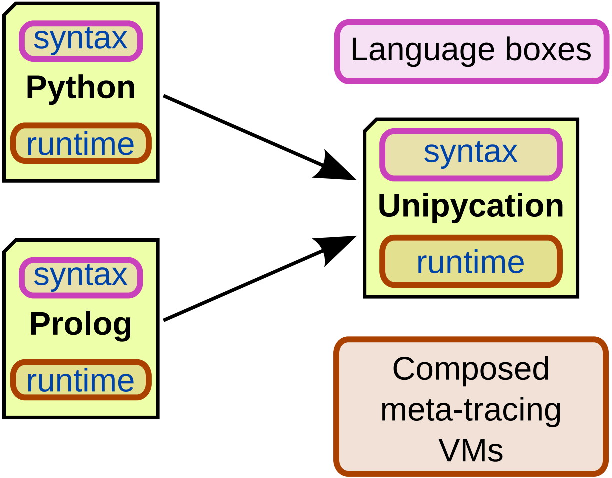
Language boxes
syntax
Unipycation
runtime

Summary


syntax
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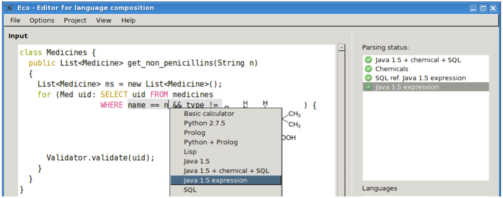
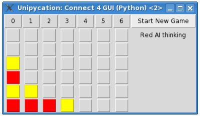
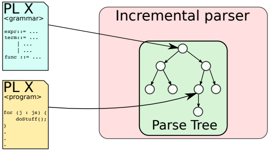
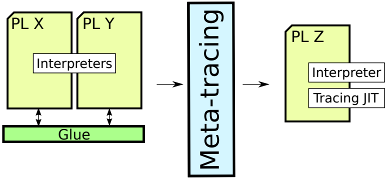
Composed meta-tracing VMs

Thanks for listening









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