VM Composition with Meta-tracing

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Intro

Language Composition

“The ability to write a computer program in a mix of programming languages.”

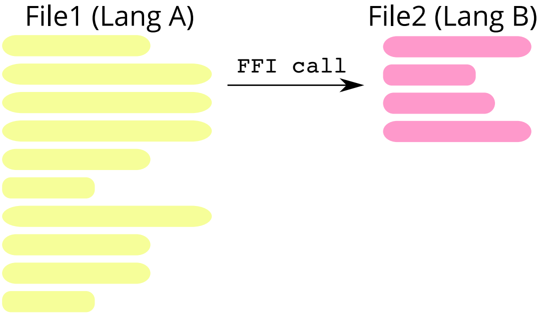
Why Compose Languages?

- Parts of a program are expressed best with different languages.

- Access to a broader set of libraries.

- Language migration.

Most languages have a Foreign Function Interface



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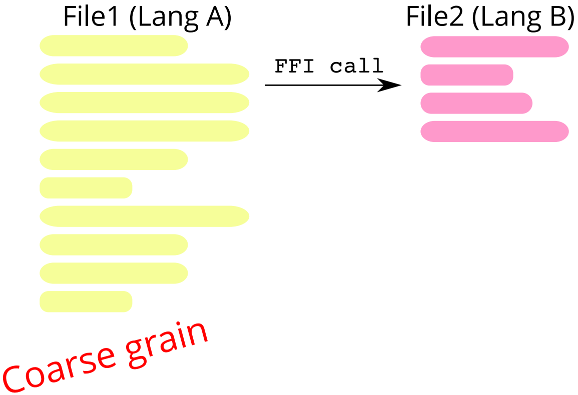
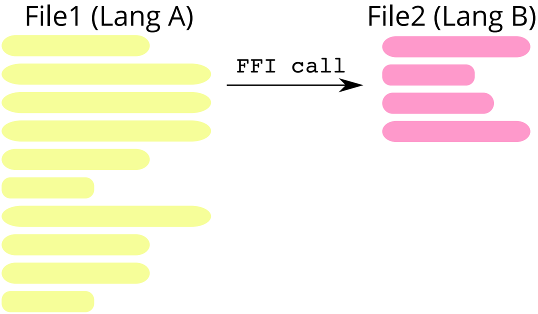


Most languages have a Foreign Function Interface

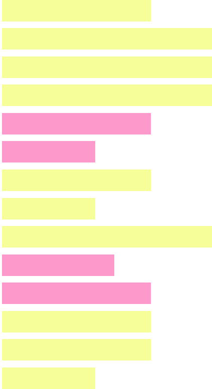


Coarse grain

Limited choice of langs

(second lang is nearly always C)

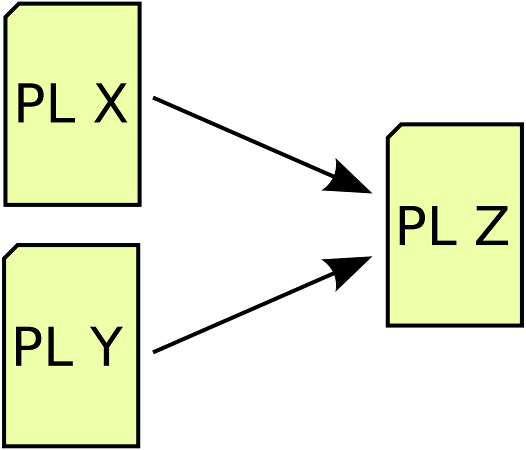
Can we do better?



- Mix languages in the same file
- Mix {methods, functions, expressions}
- Integrate scoping
- Arbitrary languages
- . . .

Approach

Breaking it Down

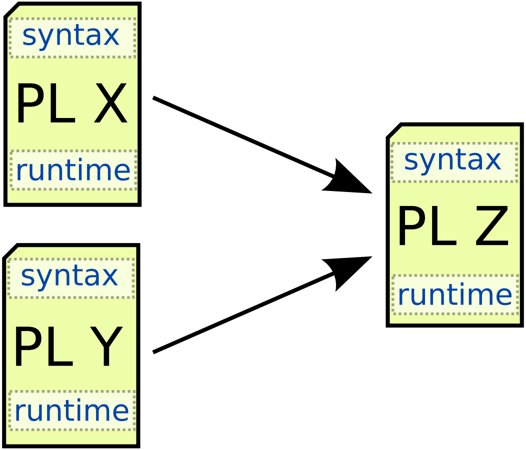


PL X

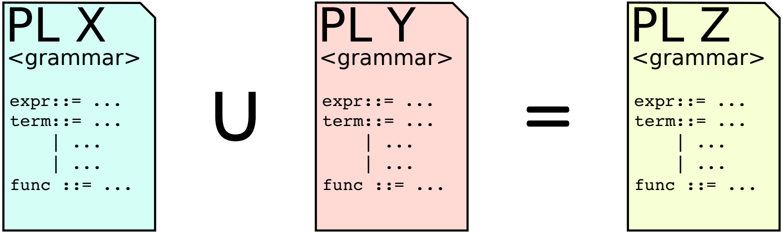
PL Y

PL Z

Breaking it Down



Composing Syntax



PL X

<grammar>

```
expr::= ...
term::= ...
    | ...
    | ...
func ::= ...
```

∪

PL Y

<grammar>

```
expr::= ...
term::= ...
    | ...
    | ...
func ::= ...
```

=

PL Z

<grammar>

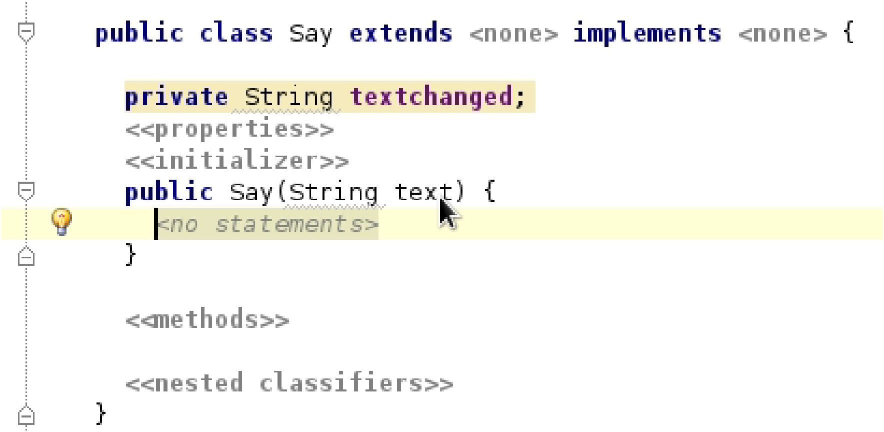
```
expr::= ...
term::= ...
    | ...
    | ...
func ::= ...
```

Easy?

Composing Syntax

- LR → Possibly undefined.
- PEG → Shadows.
- GLR → Ambiguous.

Syntax Directed Editing



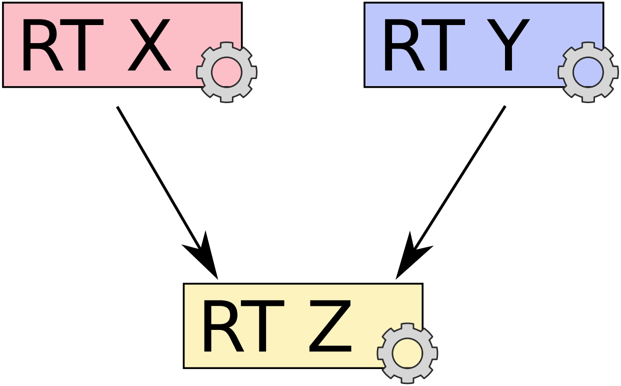
```
public class Say extends <none> implements <none> {

  private String textchanged;
  <<properties>>
  <<initializer>>
  public Say(String text) {
    <no statements>
  }

  <<methods>>

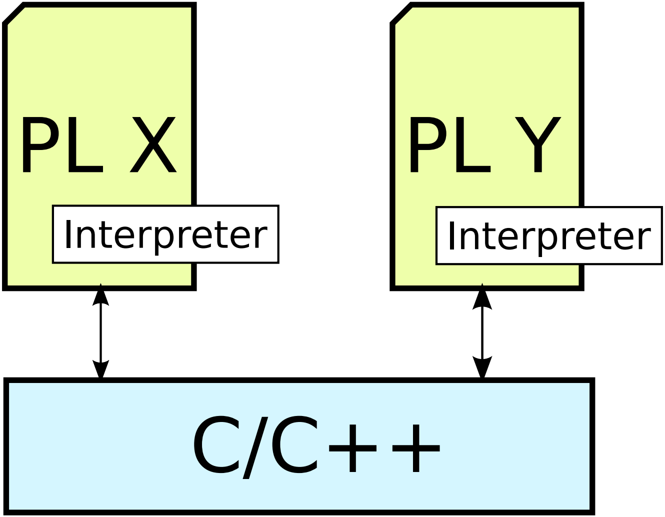
  <<nested classifiers>>
}
```

Composing Runtimes

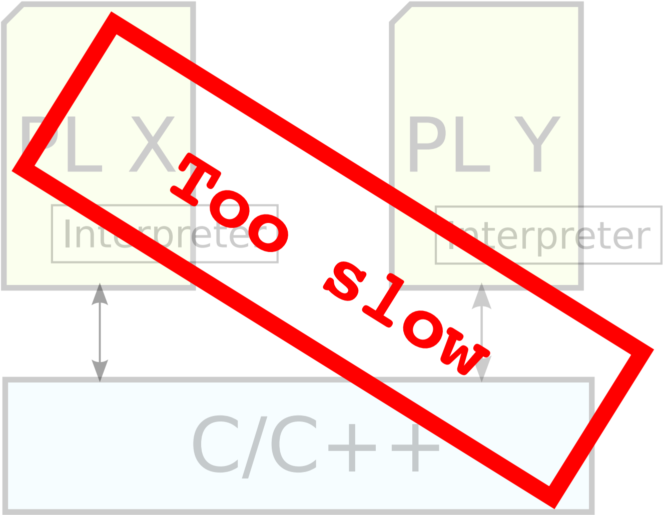


Easy?

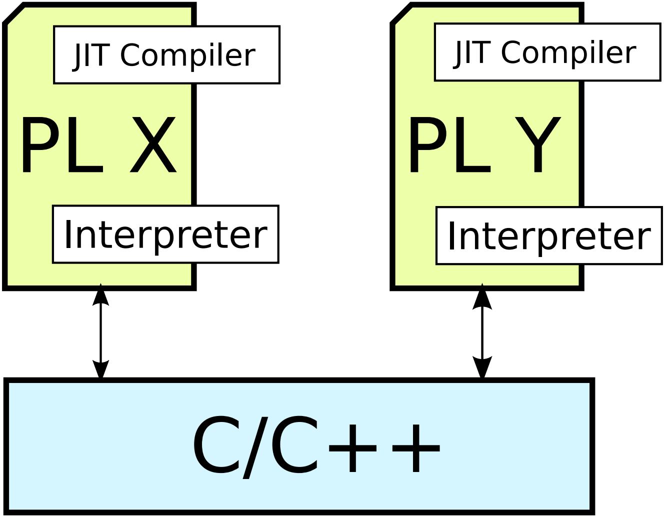
Runtime composition



Runtime composition



Runtime composition


JIT Compiler

PL X

Interpreter

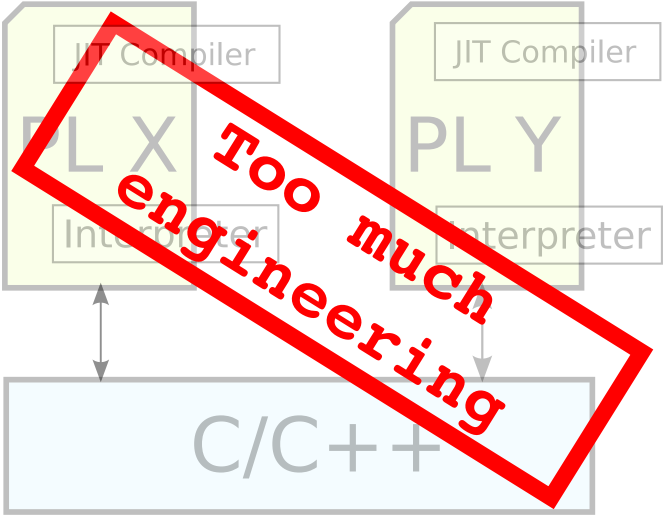
JIT Compiler

PL Y

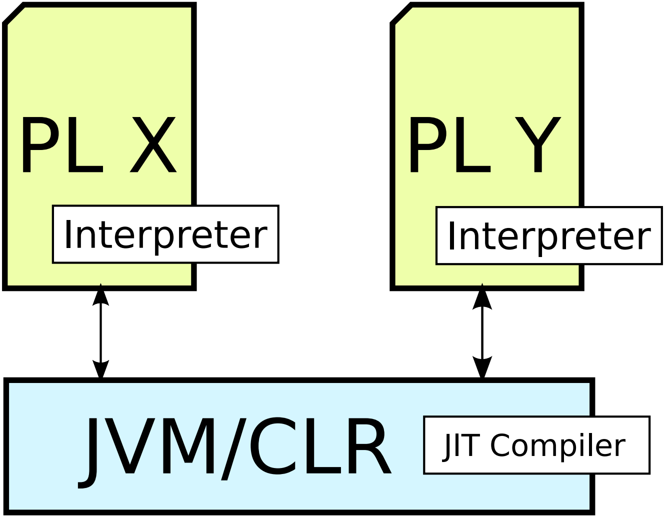
Interpreter

C/C++

Runtime composition



Runtime composition



PL X

Interpreter

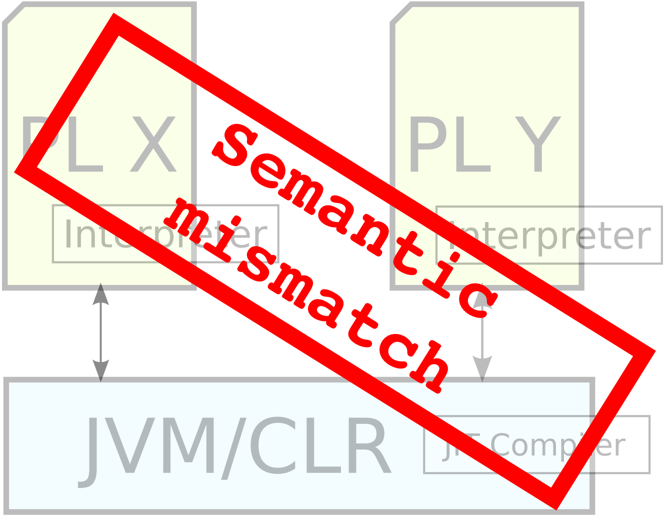
PL Y

Interpreter

JVM/CLR

JIT Compiler

Runtime composition



Our Approach

Summary:

We need a practical way of composing syntax and runtimes.

Our Approach

Summary:

We need a practical way of composing syntax and runtimes.

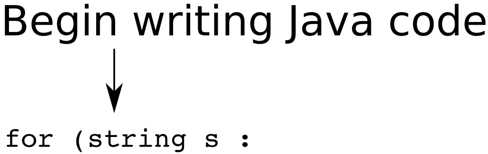
↓

Language Boxes + Meta-tracing

Language Boxes

- Borrows ideas from SDE.
- Palatable editing experience.
- Simple and practical way to compose grammars.

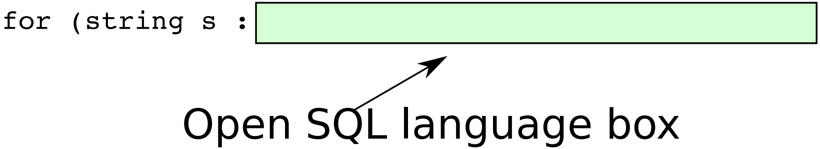
Language Boxes: E.g. Java + SQL



Begin writing Java code

```
for (string s :
```

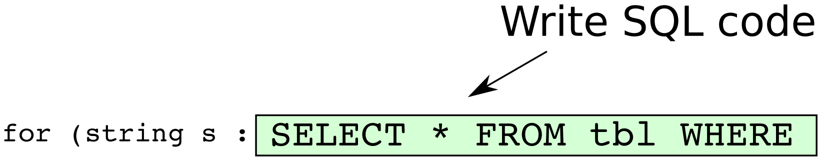
Language Boxes: E.g. Java + SQL



```
for (string s :
```

Open SQL language box

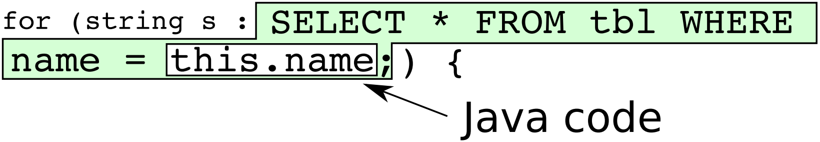
Language Boxes: E.g. Java + SQL



Write SQL code

```
for (string s : SELECT * FROM tbl WHERE
```

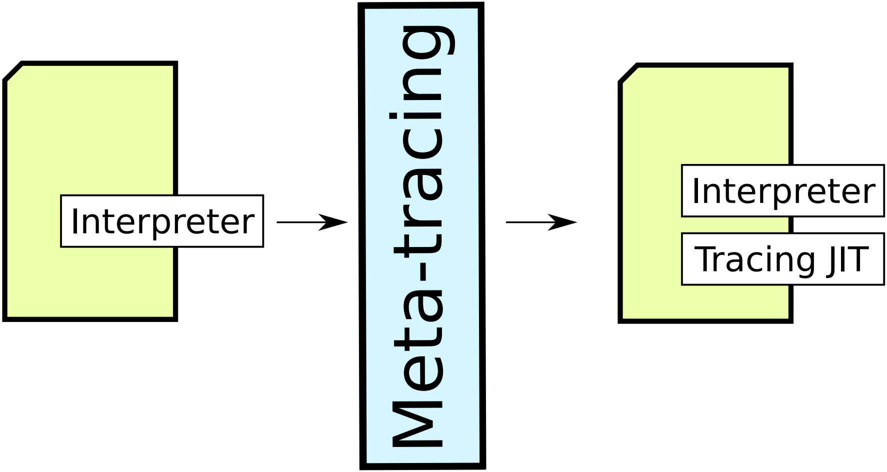
Language Boxes: E.g. Java + SQL



```
for (string s : SELECT * FROM tbl WHERE
name = this.name;) {
```

Java code

Meta-tracing



Interpreters are Loops

- Tell a meta-tracer about the interpreter loop.
- Generate a tracing JIT.
- Trace the interpreter itself, not the user program.

Adding a JIT with Meta-tracing

```
...
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 ...:
        ...
```

Adding a JIT with Meta-tracing

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

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
```

```
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
```

Meta-tracing JITs

FL Interpreter

```
program_counter = 0; stack = []
vars = {...}
while True:
  jit_merge_point(program_counter)
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```

Meta-tracing JITs

FL Interpreter

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program_counter = 0; stack = []
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  instr = load_instruction(program_counter)
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    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*)

```
assume x == 6
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

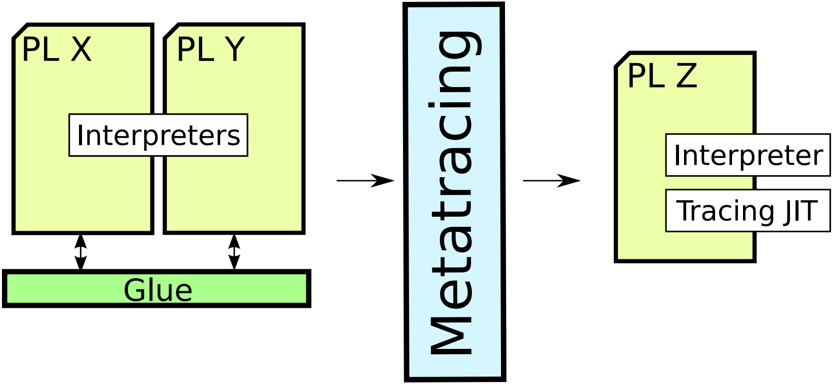
```
v0 = <program_counter>
v1 = <stack>
v2 = <vars>
v3 = load_instruction(v0)
guard_eq(v3, INSTR_VAR_GET)
v4 = dict_get(v2, "x")
list_append(v1, v4)
v5 = add(v0, 1)
v6 = load_instruction(v5)
guard_eq(v6, INSTR_INT)
list_append(v1, 0)
v7 = add(v5, 1)
v8 = load_instruction(v7)
guard_eq(v8, INSTR_LESS_THAN)
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)
```

Optimisation

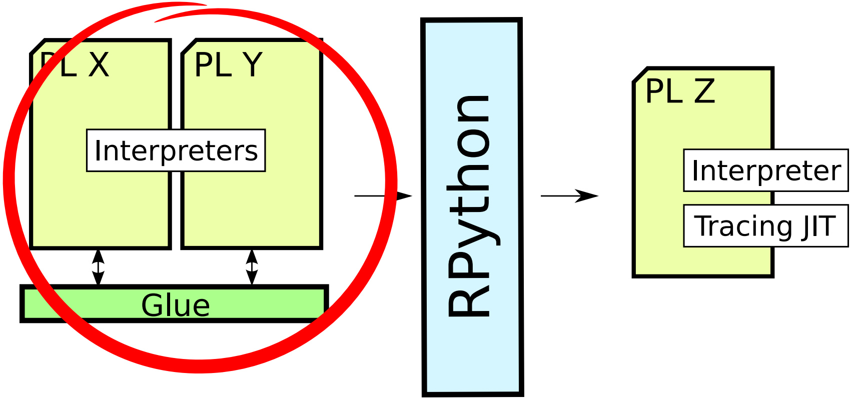
Optimised Trace

```
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)
```

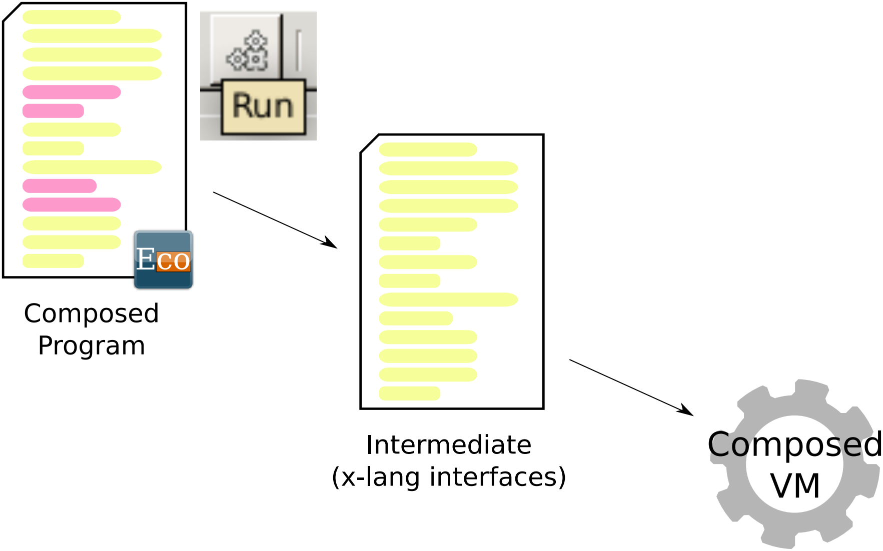
How Does this Apply to VM Composition?



How Does this Apply to VM Composition?



Putting it All Together



Composed Program

Intermediate (x-lang interfaces)

Composed VM

Summarising our Approach

- Editing with Language boxes.
  - Practical syntactic composition.
  - Traditional “code editor” look and feel.
- Interpreter Composition with Meta-tracing
  - Relatively little engineering effort.
  - Language agnostic JIT optimisations.
- Glue together editor and VM with intermediate representation.

Our Compositions

Our Language Compositions

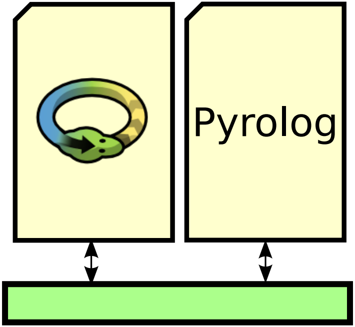
- Unipycation: Python + Prolog
- PyHyp: PHP + Python
- SQPyte: Python + SQLite

Our Language Compositions

- Unipycation: Python + Prolog
- PyHyp: PHP + Python
- SQPyte: Python + SQLite

Unipycation

Python + Prolog



Unipycation

- Fairly coarse “proof of concept” composition.
- Shows that we can glue together meta-tracing interpreters.
- Idiomatic interoperability between Python and Prolog.

Unipycation Example

```
from uni import Engine

engine = Engine("""
edge(a, c). edge(c, b). edge(c, d). edge(d, e).
edge(b, e). edge(c, f). edge(f, g). edge(e, g).
edge(g, b).

path(From, To, MaxLen, Nodes) :-
    path(From, To, MaxLen, Nodes, 1).
... """)

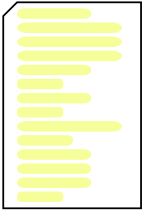
paths = engine.db.path.iter

for (to, nodes) in paths("b", None, 4, None):
    print("To %s via %s" % (to, nodes))
```

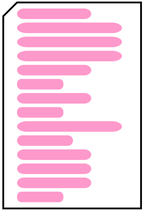
Outcomes of Unipycation

- Proved the concept
  - We wrote some fairly complex composed programs.
- Relatively little engineering effort.
- Gave fairly good performance.
  - Cross-language tracing works.

Unipycation Performance

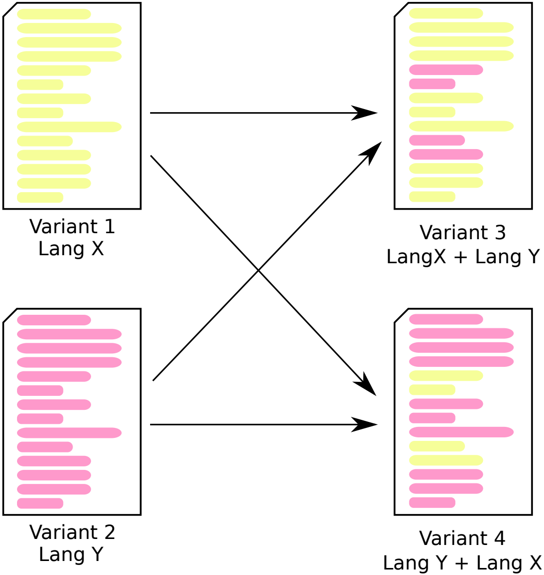


Variant 1
Lang X



Variant 2
Lang Y

Unipycation Performance



Unipycation Performance

Benchmark	$\frac{\mathit{Python}\rightarrow\mathit{Prolog}}{\mathit{Python}}$		$\frac{\mathit{Python}\rightarrow\mathit{Prolog}}{\mathit{Prolog}}$		$\frac{\mathit{Python}\rightarrow\mathit{Prolog}}{\text{Unipycation}}$
SmallFunc	1.276×	±0.081	0.201×	±0.038	1.000×
L1A0R	1.005×	±0.053	0.957×	±0.057	1.000×
L1A1R	1.072×	±0.071	1.034×	±0.069	1.000×
NdL1A1R	5.902×	±0.044	5.635×	±0.216	1.000×
TCons	6.073×	±0.106	13.471×	±0.208	1.000×
Lists	5.969×	±0.025	3.335×	±0.010	1.000×

Benchmark	$\frac{\mathit{Python}\rightarrow\mathit{Prolog}}{\mathit{Prolog}}$		$\frac{\mathit{Python}\rightarrow\mathit{Prolog}}{\text{Unipycation}}$
sat-models	1.462×	±0.021	1.000×
tube	1.014×	±0.019	1.000×
connect4	1.431×	±0.014	1.000×

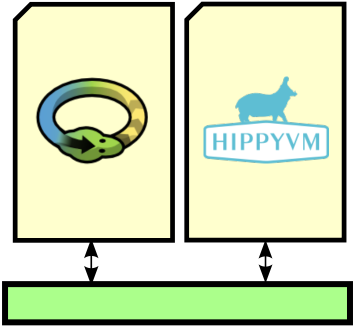
Unipycation Limitations

- Little syntactic integration.
  - Eco served little more than a syntax checker.

- Rudimentary type conversions.
  - Python objects opaque to Prolog.

PyHyp

PHP + Python



Goals of PyHyp

How far can we push language composition?

- Syntactic interoperability harnessing Eco.
- Less opaque type conversions.
- Performance <2–3× over mono-language programs.

Features of PyHyp

- Calling Python functions and methods from PHP
- Calling PHP functions and methods from Python
- Transparent type conversions
- Arbitrary nesting of foreign functions
- Python expressions in PHP
- “Embedding” Python methods inside PHP classes
- Adds support for references to Python
- Cross-language scoping
- Cross-language exceptions

PyHyp Demo

PyHyp Performance

Benchmark	HippyVM	PyHyp$_{\mathrm{PHP}}$	PyHyp$_{\mathrm{Py}}$	PyPy
instchain	0.912 ±0.0011	1.000		0.675 ±0.0007
l1a0r	1.368 ±0.0004	1.000	1.360 ±0.0003	1.340 ±0.0106
l1a1r	1.306 ±0.0017	1.000	1.303 ±0.0016	1.140 ±0.0022
lists	0.975 ±0.0020	1.000	0.560 ±0.0012	0.497 ±0.0010
ref_swap	1.000 ±0.0002	1.000	0.700 ±0.0001	
return_simple	1.000 ±0.0001	1.000	0.778 ±0.0001	0.889 ±0.0001
scopes	4.511 ±0.0025	1.000	0.929 ±0.0005	1.000 ±0.0001
smallfunc	1.000 ±0.0001	1.000	0.750 ±0.0000	1.000 ±0.0001
sum	0.999 ±0.0001	1.000	0.750 ±0.0001	0.874 ±0.0001
sum_meth	0.999 ±0.0001	1.000		0.874 ±0.0002
sum_meth_attr	0.999 ±0.0061	1.000		0.904 ±0.0057

. . .

PyHyp Performance (contd.)

Benchmark	HippyVM	PyHyp$_{\text{PHP}}$	PyHyp$_{\text{Py}}$	PyPy
. . .				
total_list	0.864 ±0.0002	1.000	1.508 ±0.0004	0.587 ±0.0003
walk_list	0.779 ±0.0011	1.000	1.601 ±0.0026	1.080 ±0.0015
deltablue	4.325 ±0.0212	1.000		0.457 ±0.0026
fannkuch	1.848 ±0.0007	1.000	1.891 ±0.0005	1.005 ±0.0004
mandel	0.921 ±0.0005	1.000	0.999 ±0.0003	
richards	0.853 ±0.0010	1.000		0.488 ±0.0005
Geometric Mean	1.222 ±0.0006	1.000	0.963 ±0.0003	0.813 ±0.0007

Worst case: 2.6x overhead

Semantic Friction

Semantic Friction

Implementing desired behaviour: relatively easy

Deciding the correct behaviours: hard

“Semantic friction”

Compromises sometimes must be made.

Semantic Friction: References

```
function swap(&$a, &$b) {
    $temp = $a;
    $a = $b;
    $b = $temp;
}

...

$x = 1; $y = 2;
swap($x, $y);
echo "$x $y";
```

Pure PHP – Prints "2 1"

Semantic Friction: References

```
@php_decor(refs=(0, 1))
def swap(a, b):
    temp = a.deref()
    a.store(b.deref())
    b.store(temp)


...

$x = 1; $y = 2;
swap($x, $y);
echo "$x $y";
```

Callee in Python

Semantic Friction: References

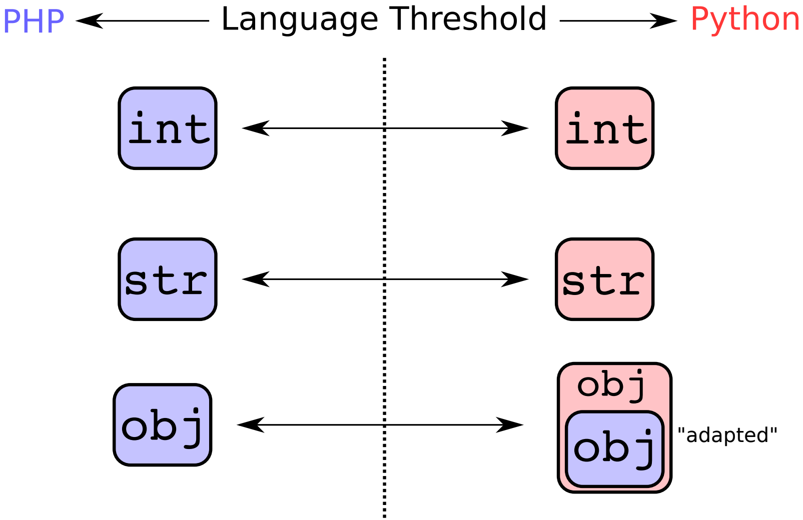
```
function swap(&$a, &$b) {
    $temp = $a;
    $a = $b;
    $b = $temp;
}

...

x = PHPRef(1); y = PHPRef(2)
swap(x, y);
print("%s %s" % (x.deref(), y.deref()))
```

Caller in Python

Semantic Friction: Array/Dict/List Conversions



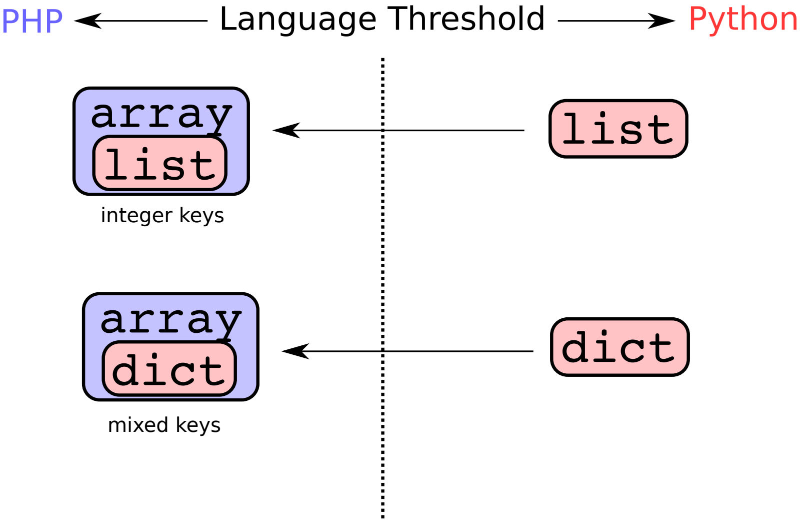
Semantic Friction: Array/Dict/List Conversions

	PHP	Python
Sequence type	`array`	`list`
Mapping type	`array`	`dict`

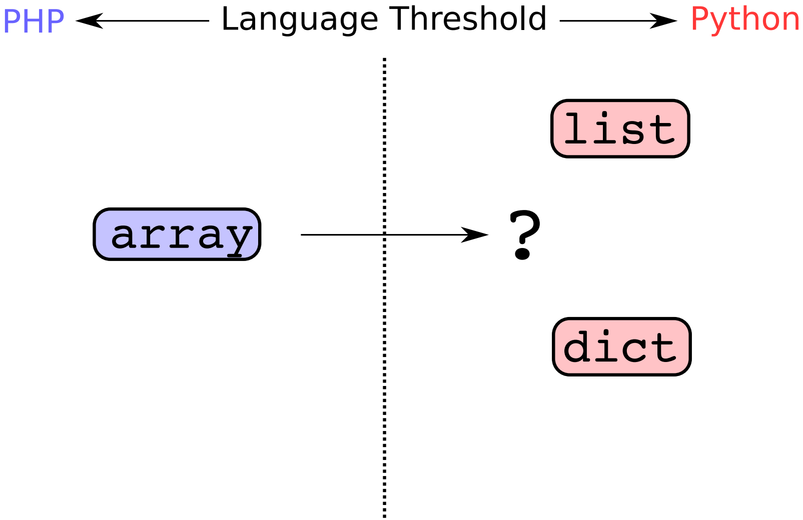
Semantic Friction: Array/Dict/List Conversions

```
php > $a = ["this", "is", "a", "list"];
php > print_r($a);
Array
(
    [0] => this
    [1] => is
    [2] => a
    [3] => list
)
```

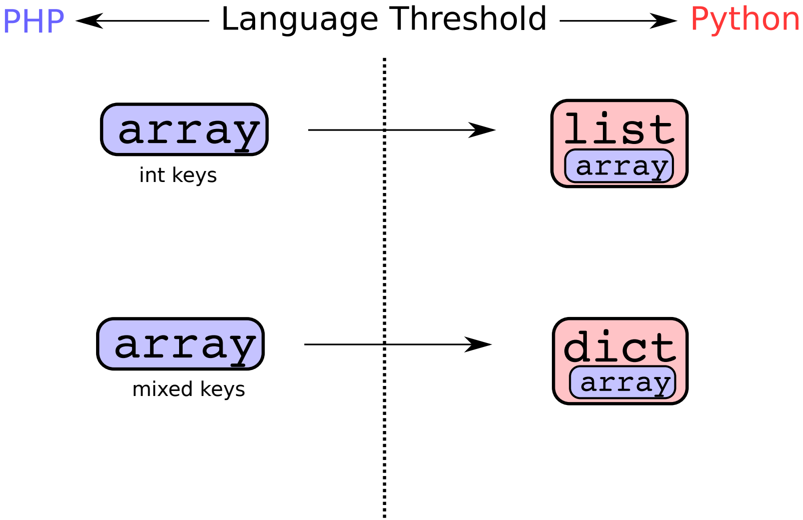
Semantic Friction: Array/Dict/List Conversions



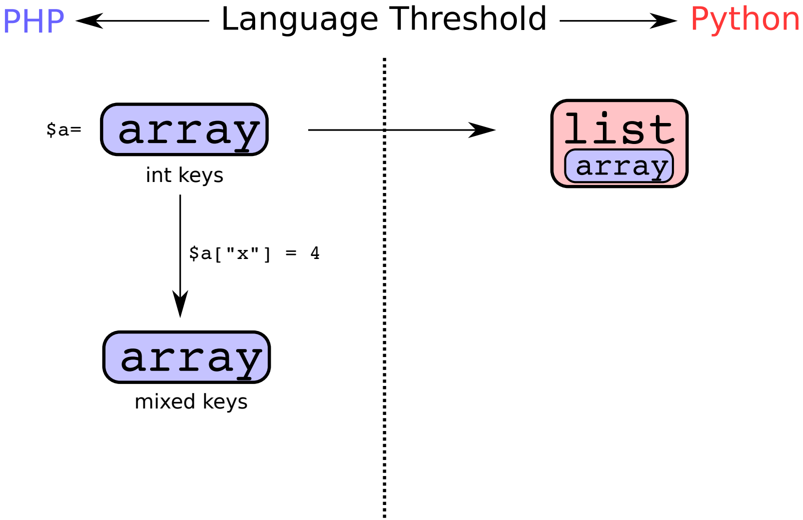
Semantic Friction: Array/Dict/List Conversions



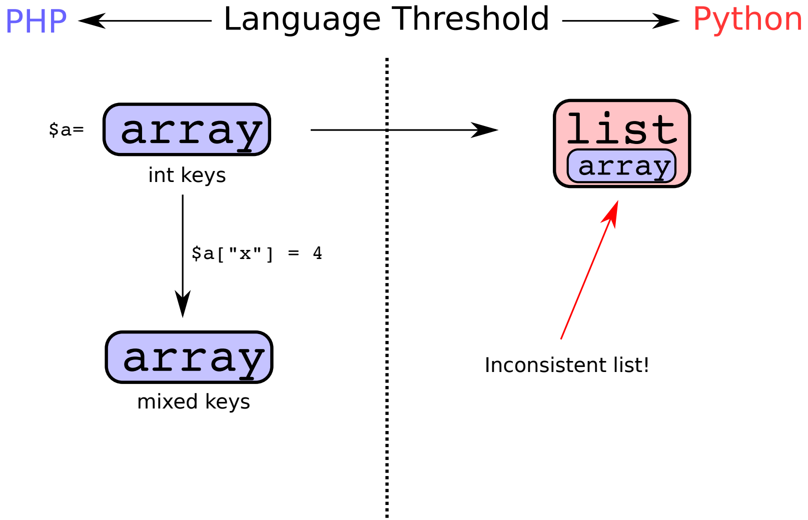
Semantic Friction: Array/Dict/List Conversions



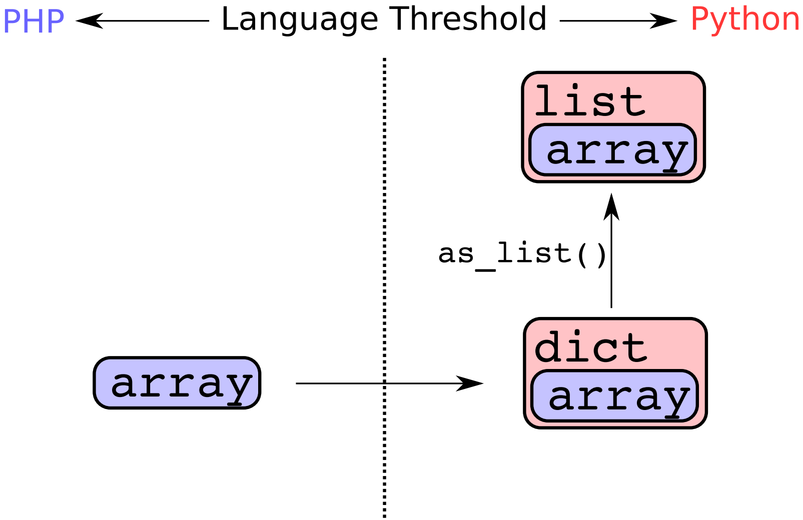
Semantic Friction: Array/Dict/List Conversions



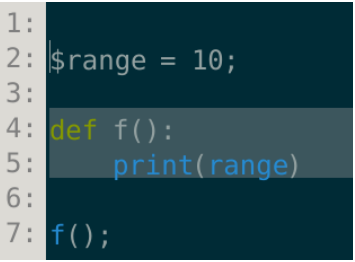
Semantic Friction: Array/Dict/List Conversions



Semantic Friction: Array/Dict/List Conversions



Semantic Friction: Cross Language Scoping



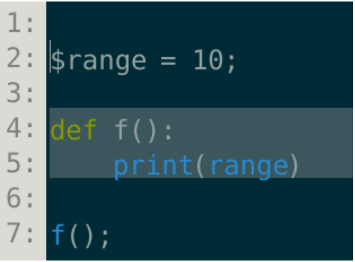
```

$range = 10;

def f():
    print(range)

f();
```

Semantic Friction: Cross Language Scoping



```

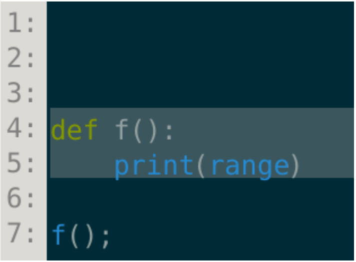
$range = 10;

def f():
    print(range)

f();
```

Should print: `10`

Semantic Friction: Cross Language Scoping



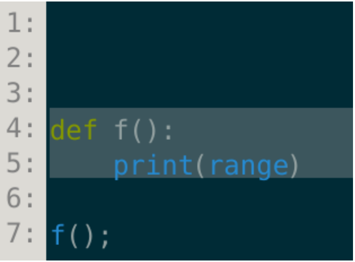
```



def f():
    print(range)

f();
```

Semantic Friction: Cross Language Scoping



```



def f():
    print(range)

f();
```

Should print: `<built-in function range>`

Semantic Friction: Cross Language Scoping

If a variable is not bound it the current box:

1. Search boxes outwards starting with the parent box.
2. Look in the "global" namespace of the current language.
3. Look in the "global" namespace of the other language.

"Globals"

- Python: {builtins}
- PHP: {functions, classes}

Conclusions

Conclusions

- Language boxes:
  - Practical syntax composition.
  - Decent editor experience.
- Meta-tracing:
  - Compositions with relatively little effort.
  - Good performance.
- Implementing x-lang behaviours is easy.
- Designing x-lang behaviours is hard.
  - Semantic friction.

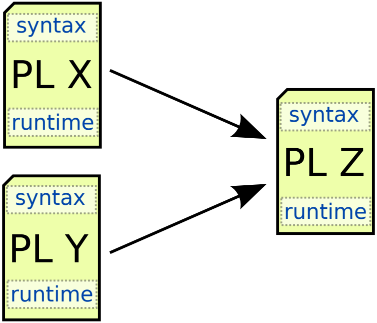
Future Work

- Tools for composed programs
  - Debugging
  - Profiling
  - Version control
  - ...
- Statically typed/functional languages.
- Compositions with $>$2 languages involved.

References

- *Parsing Composed Grammars with Language Boxes* Lukas Diekmann, Laurence Tratt.
- *Eco: A Language Composition Editor* Lukas Diekmann, Laurence Tratt.
- *Unipycation: A Case Study in Cross-language Tracing*, Edd Barrett, Carl Friedrich Bolz and Laurence Tratt
- *Approaches to Interpreter Composition*, Edd Barrett, Carl Friedrich Bolz and Laurence Tratt
- *Fine-grained Language Composition: A Case Study*, Edd Barrett, Carl Friedrich Bolz, Lukas Diekmann, Laurence Tratt
- *Making an Embedded DBMS JIT-friendly*, Carl Friedrich Bolz, Darya Kurilova, Laurence Tratt

Thanks



Language Boxes + Meta-tracing

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
  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
```

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
```

Meta-tracing JITs

FL Interpreter	User program (lang *FL*)

```
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
```

```
assume x == 6
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)
...
```

Meta-tracing JITs

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

```
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)
```

Dict 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)
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.