Interpreter Taming to Realize Multiple Compilations in a Meta-Tracing JIT Compiler Framework

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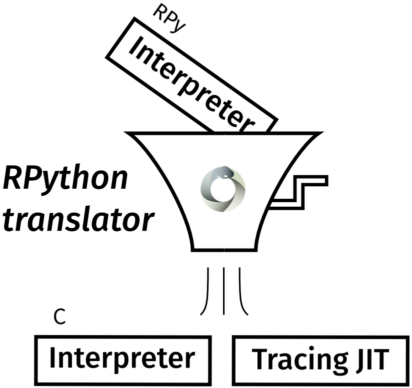
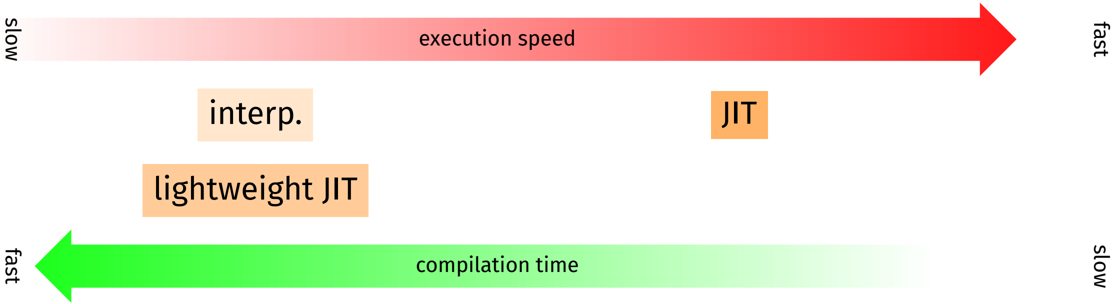
Background: RPython [Bol+09]

- A language implementation framework to develop a high-performance virtual machine (VM)
  - Generate a VM w/ tracing JIT compiler from an interpreter
- Used for generating several VMs such as PyPy [RP06], Pycket [Bau+15], and so forth



Background: Modern VMs Employ Multilevel Compilation

- Supported in modern VMs such as HotSpot$_{TM}$, V8, and so forth
- Balances code quality and compilation time by changing compilation levels

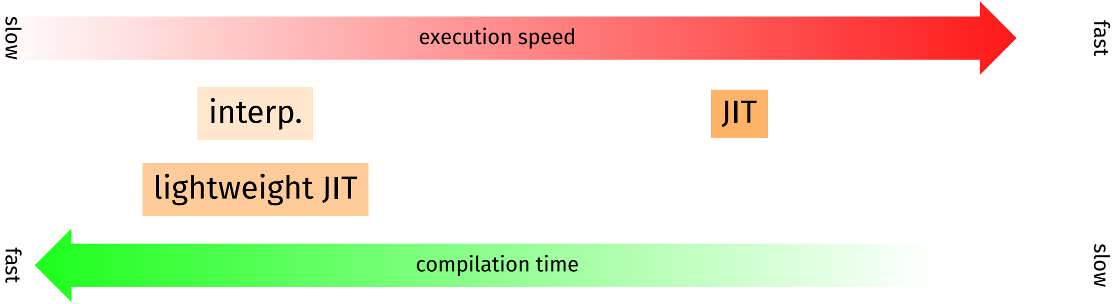


short-lived app.
e.g., batch-process

long-lived app.
e.g., server-side.

Background: Modern VMs Employ Multilevel Compilation

- Long-lived programs are applied to a JIT compiler
  - generating quality code but consuming compilation time



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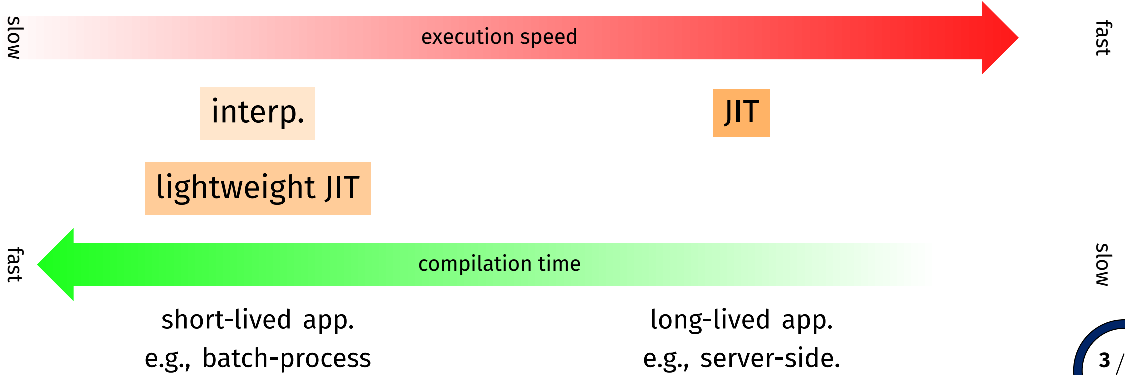
e.g., batch-process

long-lived app.
e.g., server-side.

Background: Modern VMs Employ Multilevel Compilation

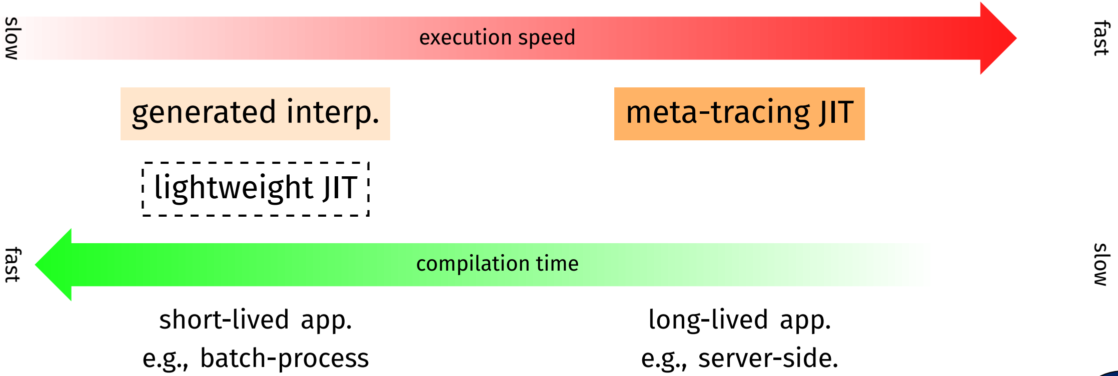
- Long-lived programs are applied to a JIT compiler
  - generating quality code but consuming compilation time
- Short-lived programs need to be run with a lightweight compiler
  - generating code quickly



RPython is Not Yet Competitive w/ Language-Specific VMs

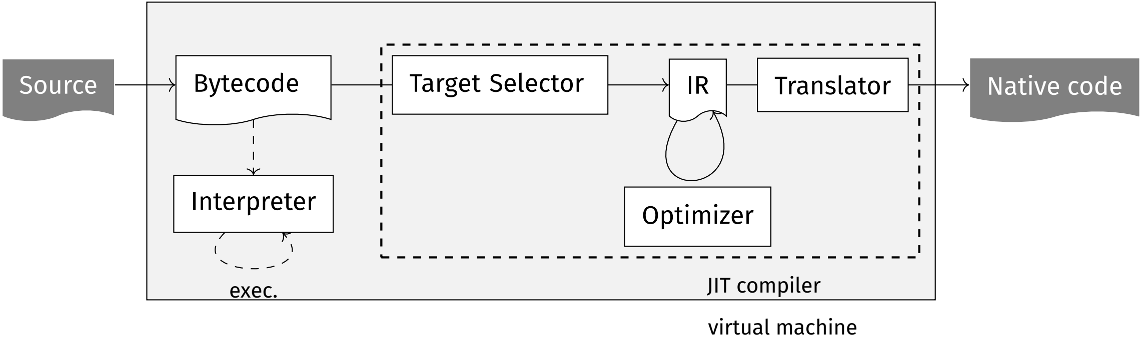
We support

- *In particular*: no support for multilevel compilation on RPython
  - *Dilemma*: hard to extend generated VMs from RPython



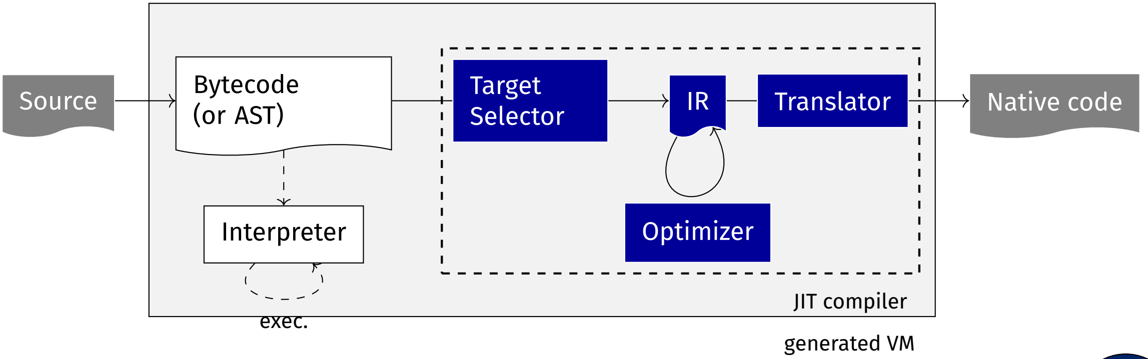
Dilemma: Hard to Extend Generated VMs (1)

- In a language-specific VM, all components are manageable



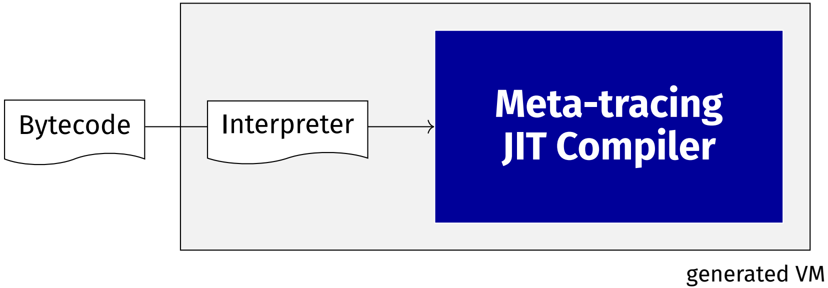
Dilemma: Hard to Extend Generated VMs (2)

- *Dilemma*: In RPython, only an interpreter (and bytecode compiler) can be managed
  - How to add lightweight compilation to RPython w/ lower effort?



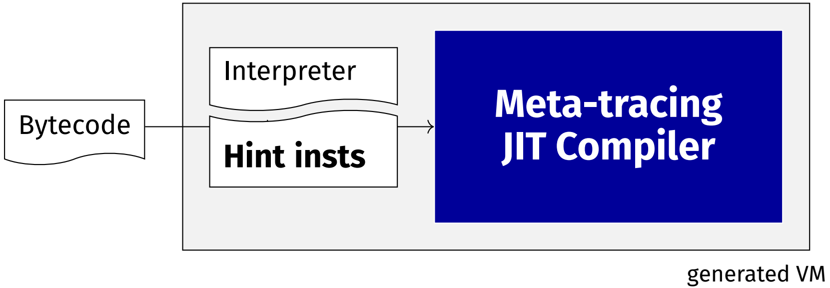
How to Add Lightweight Compilation to Meta-Tracing JIT w/ Lower Effort?: Hint instruction-based Approach

- *Approach*: control the behavior of meta-tracing JIT by inserting **hint instructions** into an interpreter, not creating compilers from scratch



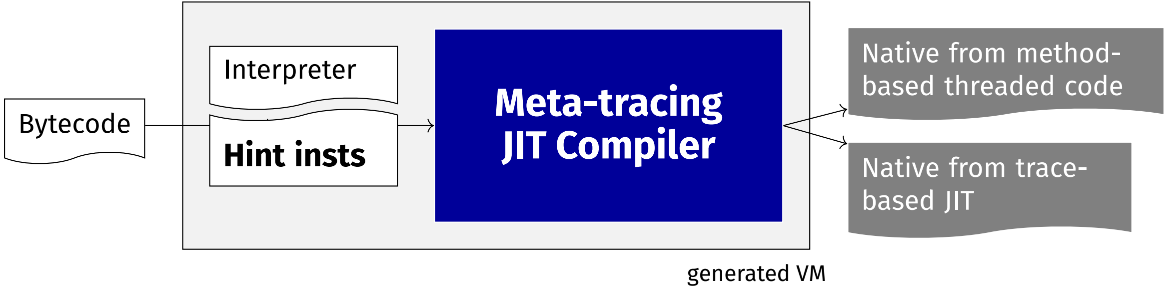
How to Add Lightweight Compilation to Meta-Tracing JIT w/ Lower Effort?: Hint instruction-based Approach

- *Approach*: control the behavior of meta-tracing JIT by inserting **hint instructions** into an interpreter, not creating compilers from scratch
  - **Hint instruction**: a pseudo function that can influence the behavior of meta-tracing JIT



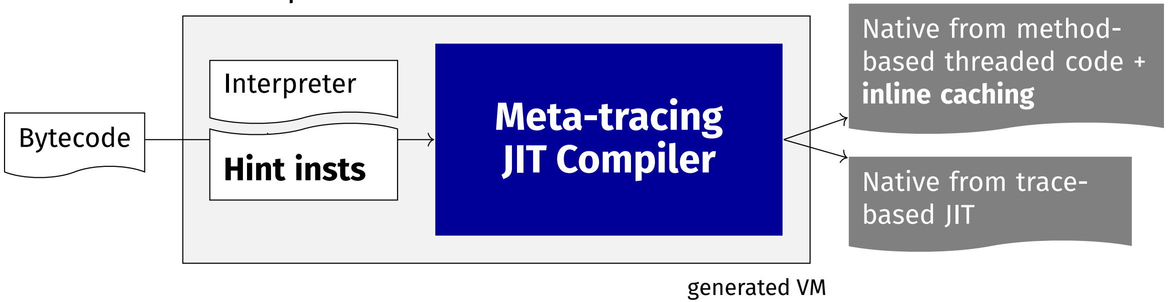
How to Add Lightweight Compilation to Meta-Tracing JIT w/ Lower Effort?: Hint instruction-based Approach

- *Previous work*: add threaded code generation to meta-tracing JIT [JOT ’22]



How to Add Lightweight Compilation to Meta-Tracing JIT w/ Lower Effort?: Hint instruction-based Approach

- *Previous work*: add threaded code generation to meta-tracing JIT [JOT '22]
- *This work*: realize inline caching [DS84] in threaded code generation and multilevel compilation



Proposal: Multilevel RPython

Interpreter w/
hint instructions

User writes

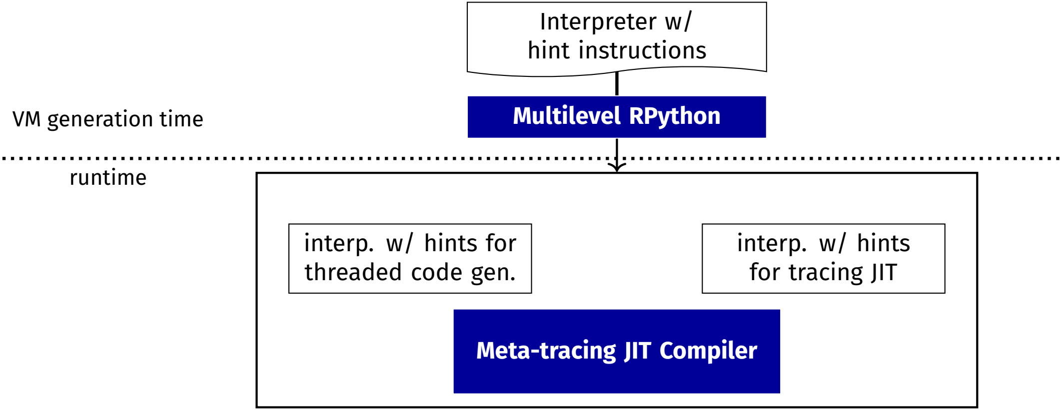
VM generation time

Multilevel RPython

runtime

Proposal: Multilevel RPython

- Each interpreter represents each compilation level



Proposal: Multilevel RPython

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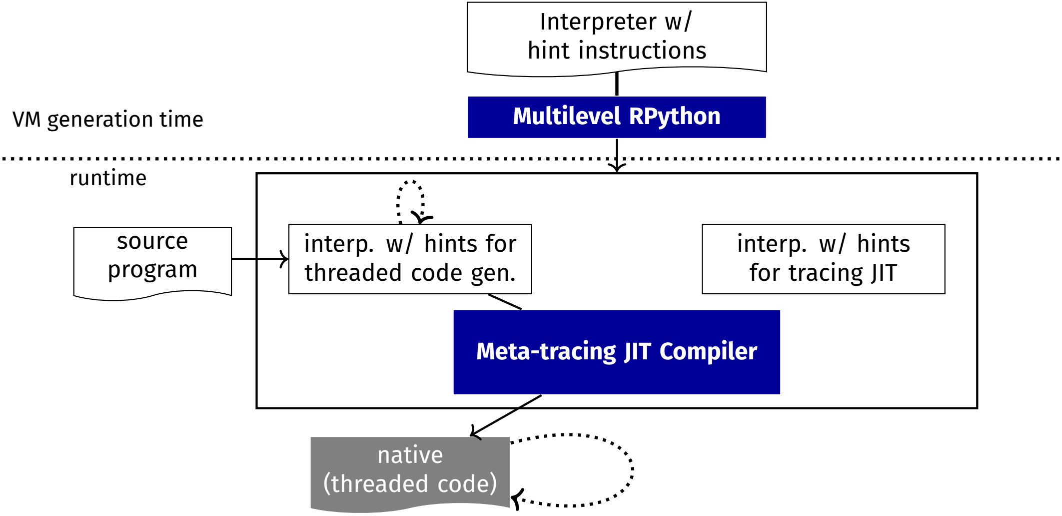

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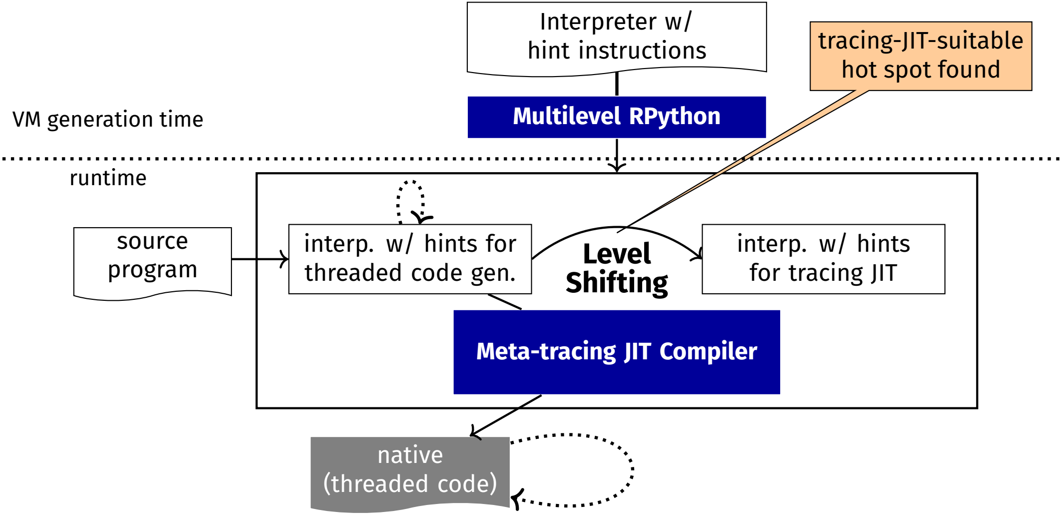

Proposal: Multilevel RPython

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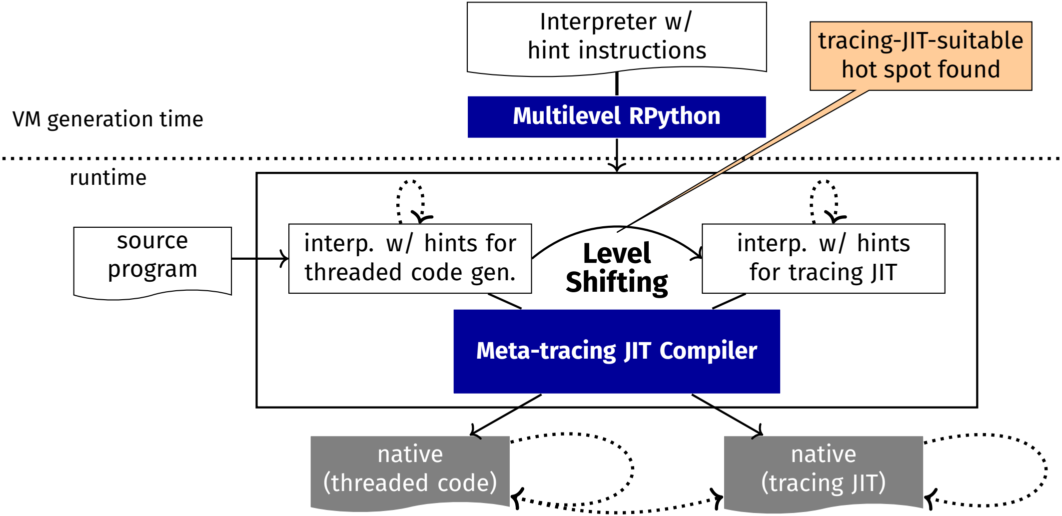


Level Shifting Between Threaded Code Gen. and Tracing JIT

Interpreter Shifter

```
def interp(..)
  while True:
    try:
      result = interp_threaded(pc)
    catch ContinueInTracing as e:
      pc = e.pc

    try:
      result = interp_tracing(pc)
    catch ContinueInThreaded as e:
      pc = e.pc
```

entry

level up

level down

Interpreter for threaded code generation

```
def interp_threaded(pc):
  threaded_driver.can_enter_jit(..)
  while True:
  instr = bytecode[pc++]
  if instr == JUMP_BACKWARD:
    if bytecode.counts[pc] > THRESHOLD:
      raise ContinueInTracing(pc)
    bytecode.couts[pc] += 1
    pc = bytecode[pc++]
  elif ..
```

Profiles the exec.

```
if exceeds threshold:
    start lightweight
    compilation
```

Interpreter for tracing JIT compilation

```
def interp_tracing(pc):
  while True:
  instr = bytecode[pc++]
  if instr == JUMP_BACKWARD:
    if bytecode.counts[pc] ≤ THRESHOLD:
      raise ContinueInThreaded(pc)
    bytecode.couts[pc] += 1
    pc = bytecode[pc++]
    tracing_driver.can_enter_jit(..)
  elif ..
```

Profiles the exec.

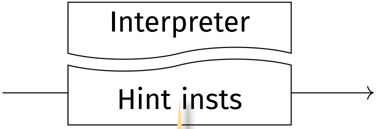
```
if exceeds threshold:
    start heavyweight
    compilation
```

Brief Recap: Threaded Code Generation [JOT '22]

- Generate threaded code [Bel73] by inserting hint instructions into an interpreter
  - 👍 small code size and short compilation time
  - ⚠ method calls in threaded code was slow (next)

Bytecode

```
L0:
  INC
  JUMP_IF L1
  INC
  JUMP L0
L1:
  CALL "g"
  RET
```



Shallow Tracing and Traversal Stack

Trace styled w/ threaded code

```
L0:
  call(INC)
  guard_false(.., L1)
  call(INC)
  jump(L0)
L1:
  call(CALL("g"))
  finish(..)
```

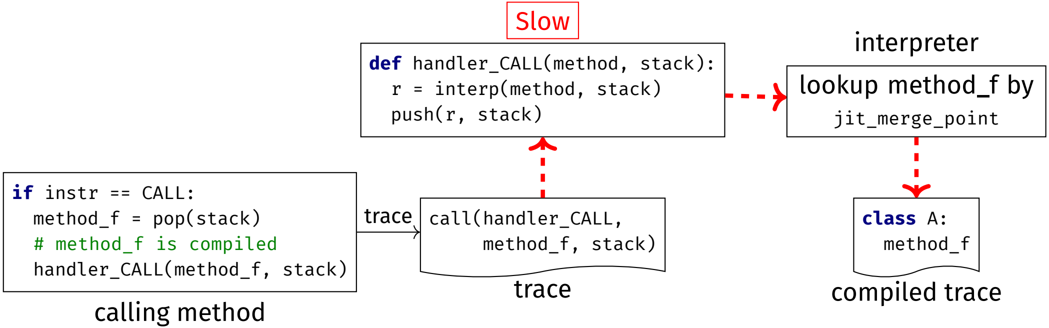
Method-based

Asm output

```
L0:
  call INC
  jnz  L1
  call INC
  jmp  L0
L1:
  call CALL
  ret
```

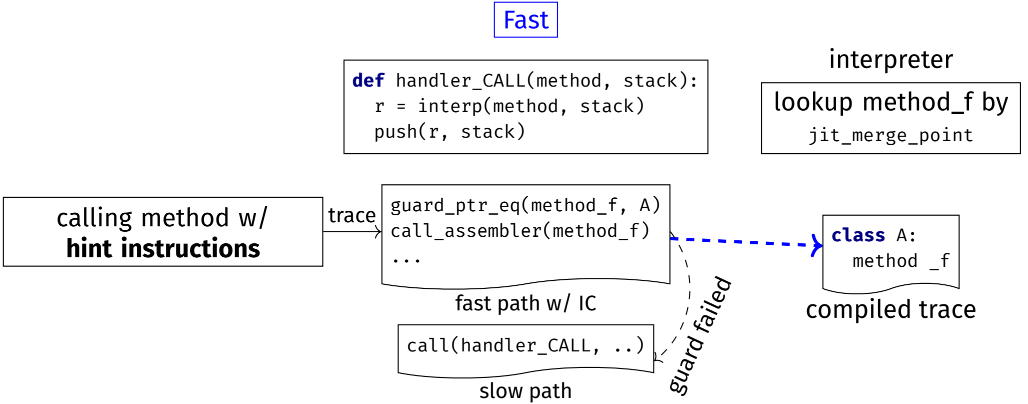
Technical Problem: Method Calls in Threaded Code Was Slow

- Every time go into the system method lookup routine of `jit_merge_point`



Solution: Inline Caching w/ Hint Instructions

- Convert into a direct call by inline caching w/ hint instructions



Inline Caching w/ Hint Instructions

- *Technique*: tame interpreter w/ hint instructions
  - record the runtime type of a `method` during interpretation
  - verify the runtime type of a `method`
  - call `call_assembler` at `CALL` when the verification passed

```
def handler_CALL(stack):
  method = pop(stack)
  if we_are_interpreted():
    record_tbl[pc] = method.type
```

```
...
guard_ptr_eq(method_f, A)
r = call_assembler(method, stack)
setitem(r, stack)
...
```

fast path

```
call(handler_CALL, ..)
...
```

slow path

Inline Caching w/ Hint Instructions

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```
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guard_ptr_eq(method_f, A)
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setitem(r, stack)
...
```

fast path

```
while True:
  instr = bytecode[pc++]
  if instr == CALL:
      method_f = pop(stack)
      if check_typ(method_f, pc):
```

```
call(handler_CALL, ..)
...
```

slow path

Inline Caching w/ Hint Instructions

- *Technique*: tame interpreter w/ hint instructions
  - record the runtime type of a `method` during interpretation
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```
...
guard_ptr_eq(method_f, A)
r = call_assembler(method, stack)
setitem(r, stack)
...
```

fast path

```
if check_typ(method_f, pc):
  r = call_assembler(method_f, stack, ..)
  push(r)
else:
  handler_CALL(stack, pc, ..)
```

```
call(handler_CALL, ..)
...
```

slow path

Inline Caching w/ Hint Instructions

- *Technique*: tame interpreter w/ hint instructions
  - record the runtime type of a `method` during interpretation
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      if check_typ(method_f, pc):
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        push(r)
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```

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r = call_assembler(method, stack)
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...
```

fast path

```
call(handler_CALL, ..)
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```

slow path

Implementation

- Implemented on PySOM
  - PySOM: A subset of Smalltalk implementation by RPython
    - 14000 LOC in RPython
- 10 out of 72 instructions are instrumented to do threaded code generation
  - `jump_on_false`, `jump_backward`, `return_local`, ...
- Total LOC:
  - PySOM: about 450 LOC addition
  - RPython: about 600 LOC addition

Evaluation and Experiment: Overview

Micro-Benchmark Evaluation

- Evaluate the cost and benefit of two JITs: threaded code generation (+ inline caching) and tracing JIT

Multilevel Experiment in a Simulated Real-World Workload

- Evaluate the performance of multilevel compilation in RPython against single level compilation
  - Multilevel: threaded code + tracing JIT
  - Single level: tracing JIT

Micro-benchmark Evaluation: What is Evaluated?

Evaluate the cost and benefit of two different JITs

threaded code generation and tracing JIT

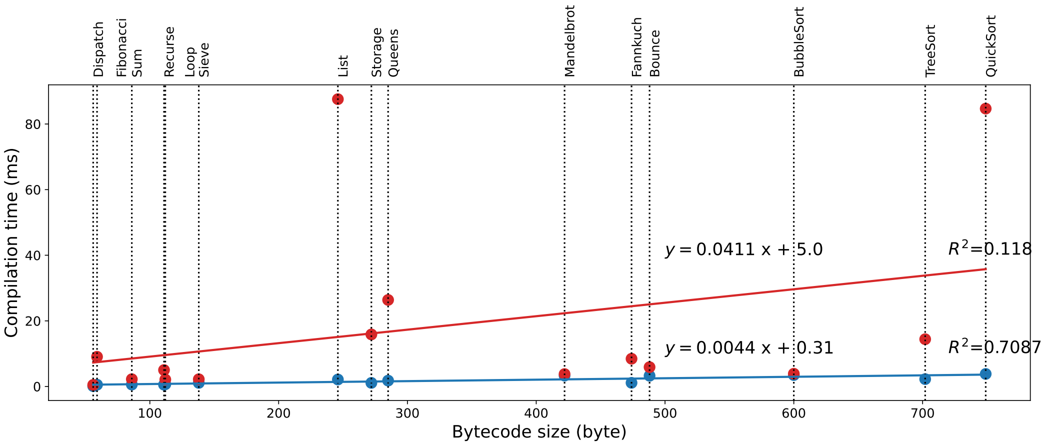
- Cost: compilation time
  - Correlation between bytecode size and compile time
- Benefit: peak performance at steady state
  - Comparison with interpreter execution

Targets

- Targets: PySOM original + Are We Fast Yet? [MDM16] micro benchmark
- Methodology: Ran 2000 times in one set for each program, iterated 30 sets

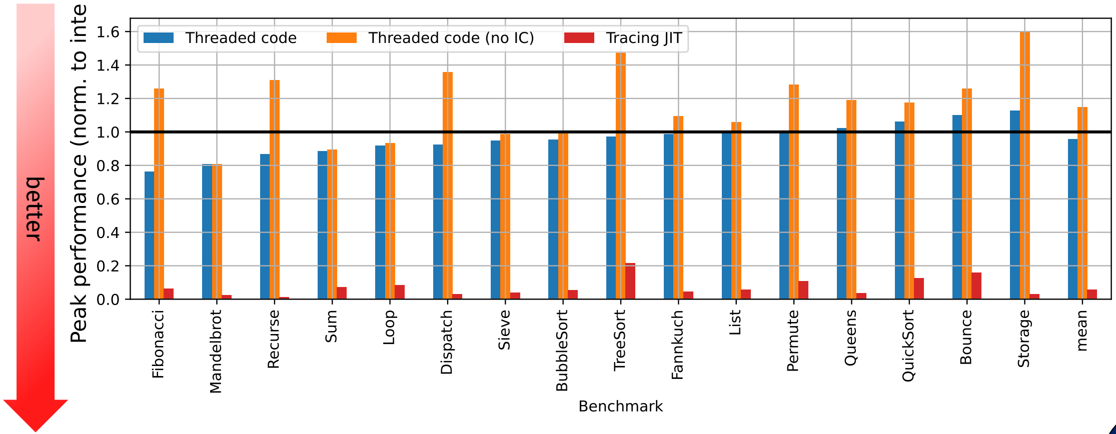
Compilation Time and Bytecode Sizes

- Threaded code: compilation time is proportional to bytecode size
- Tracing JIT: unstable



Peak Performance at Steady State

- *Overall*: threaded code was 4 % faster than interpreter, 94 % slower than tracing JIT
  - Inline caching improved threaded code approx. 20 %

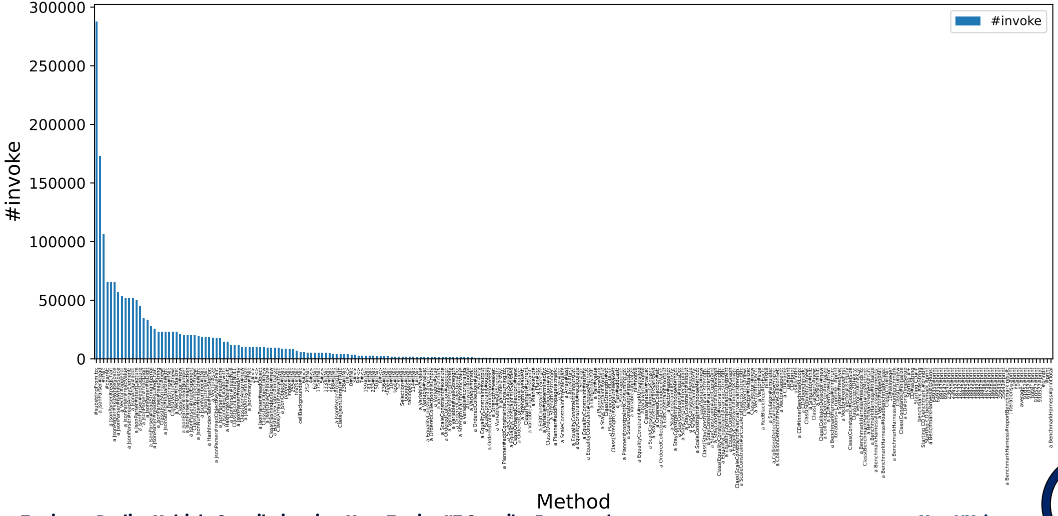


Multilevel JIT Experiment: Is Adding Threaded Code Generation Beneficial for RPython?

- Experimentation in real-world applications is currently difficult
  - difficult to access to the enterprise app, current implementation size
- Simulated a real-world workload w/ large benchmarks
  - Richards + Json + CD + DeltaBlue

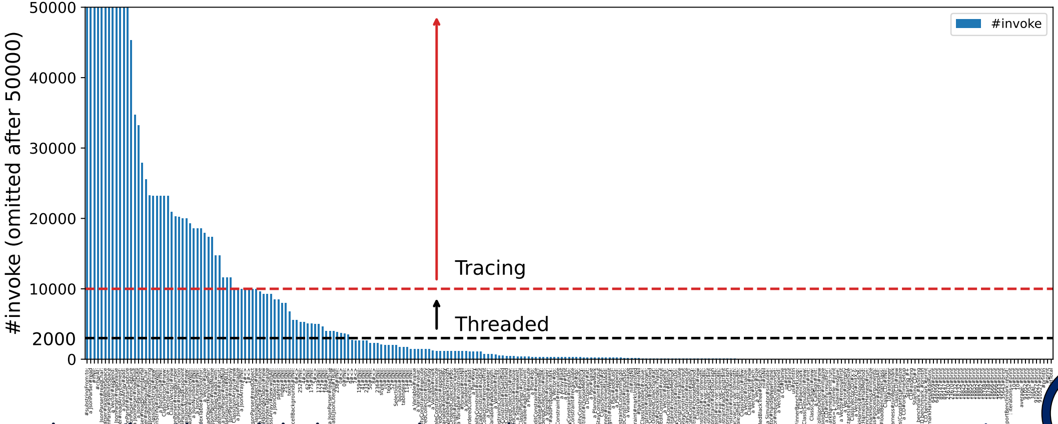
#Invocation: Simulated Larger Application

- Simulated Application: Richards + Json + CD + DeltaBlue



#Invocation: Threshold for Simulated Larger App

- Determined by the following heuristics:
  - about 30% of the methods are compiled by threaded code
  - about 20% are by tracing JIT
- Based on the result of DaCapo benchmark [Bla+06]



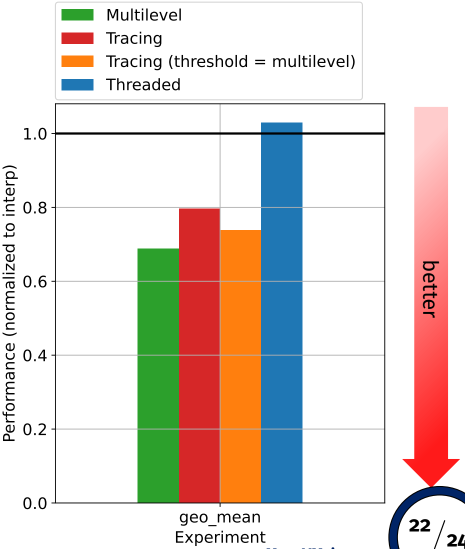
Performance: Simulated Larger Application

Result

- Multilevel is the fastest
  - about 14 % faster than tracing
  - about 5 % faster than tracing (w/ same threshold to multilevel)

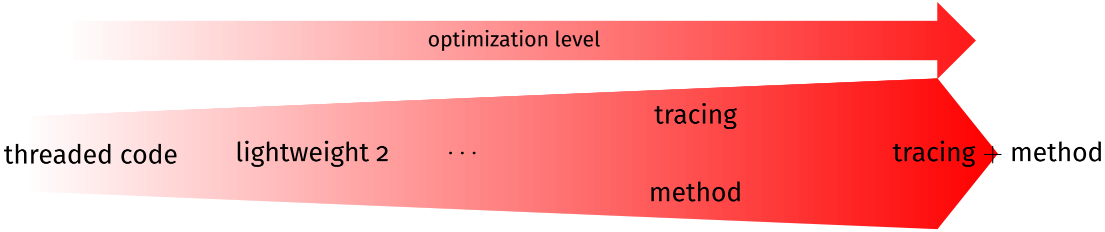
Policy	compile time	elapsed time	comp / elapse
Multilevel	66ms	90ms	0.73
Tracing	73ms	104ms	0.70
Tracing (same threshold)	62ms	94ms	0.65
Threaded	32ms	135ms	0.23
Interpreter	0ms	131ms	0

Policy	Loop threshold	Function threshold
Multilevel	1539	2039
Tracing	1039	1639



Adaptive Compilation in RPython

Perform multilevel compilation with “one interpreter” and “one engine”



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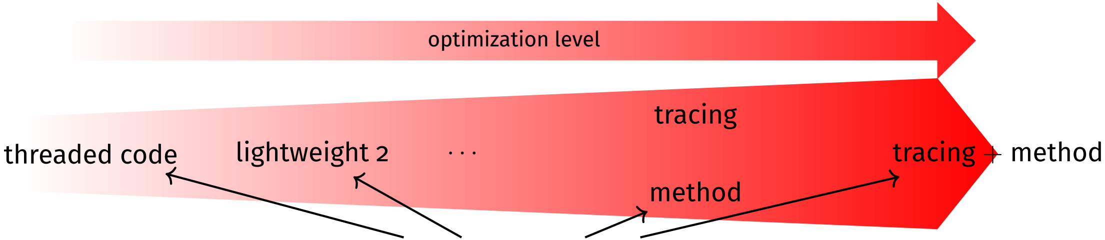

one generic interp. → common interp + a bit different definitions

Adaptive Compilation in RPython

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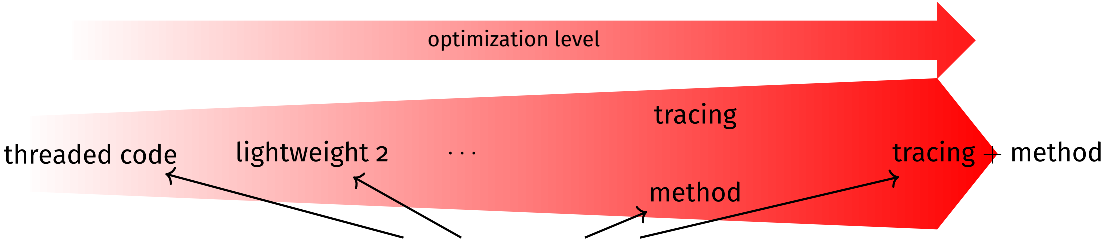

one generic interp. → common interp + a bit different definitions

perform on **one engine** = RPython

Conclusion

- Showed it is possible to add a new behavior in a meta-tracing JIT compiler framework by using hint instructions
  - threaded code generation [JOT '22]
  - inline caching [This talk]
- Multilevel compilation showed 14% better overall performance in the application that simulated a real-word workload than tracing-JIT-only compilation

How to Reduce the RPython's Compilation Time

Initial trace is so long on tracing recursive calls

```
pc = 0; bytecode = [..]; stack = [..]
while True:
  instr = bytecode[pc++]
  if instr == INT:
    n = ord(bytecode[pc++])
    push(stack, n)
  elif instr == LT:
    y, x = pop(stack), pop(stack)
    if x < y: push(stack, True)
    else: push(stack, False)
  elif instr == JUMP_IF:
    if not top(stack):
    pc = bytecode[pc++]
  elif instr == JUMP_BACK:
    pc = bytecode[pc++]
  elif instr == CALL:
    target = bytecode[pc++]
    r = interp(stack, target)
    push(r)
  elif ..
```

```
def sum(x):
  if x < 1: return 1
  else:
    return n + sum(n-1)
```

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```
def sum(x):
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```
v4 = list_read(v3, v0)
v5 = add(v0, 1)
guard_eq(v4, LT)
v6 = add(v5, 1)
v7 = list_pop(v1)
v8 = list_pop(v1)
guard_type(v7, int)
guard_type(v8, int)
guard_not_less_than(v7, v8)
list_append(v1, False)
v10 = list_read(v3, v0)
guard_eq(v10, DUP)
...
guard_eq(v18, SUB)
...
guard_ed(v26, CALL)
... (inlined) ...
guard_eq(v34, DUP)
...
auard_eq(v42, SUB)
...
... (stop inlining) ...
...
guard_eq(v58, CALL)
v1092 = call("sum", ..)
...
finish(v2000)
```

How to Reduce the RPython's Compilation Time

RPython consumes time on ..

- inlining a user program's function call

Initial trace

```
v4 = list_read(v3, v0)
v5 = add(v0, 1)
guard_eq(v4, LT)
v6 = add(v5, 1)
v7 = list_pop(v1)
v8 = list_pop(v1)
guard_type(v7, int)
guard_type(v8, int)
guard_not_less_than(v7, v8)
list_append(v1, False)
v10 = list_read(v3, v0)
guard_eq(v10, DUP)
...
guard_eq(v18, SUB)
...
guard_ed(v26, CALL)
... (inlined) ...
guard_eq(v34, DUP)
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guard_eq(v42, SUB)
...
... (stop inlining) ...
...
guard_eq(v58, CALL)
v1092 = call("sum", ..)
...
finish(v2000)
```

How to Reduce the RPython's Compilation Time

RPython consumes time on ..

- inlining a user program's function call
- optimizing the initial trace

Optimized trace (constants and lists are folded)

```
v6 = list_pop(v1)
guard_type(v6, int)
guard_not_less_than(v6, 1)
v16 = dict_get(v2, "n")
guard_type(v16, int)
v21 = int_sub(v16, 1)
... (inlined) ...
finish(v64)
```

How to Reduce the RPython's Compilation Time

RPython consumes time on ..

- inlining a user program's function call
- optimizing the initial trace
- recompiling after guard failure (if failed many times)

Optimized trace (constants and lists are folded)

```
v6 = list_pop(v1)
guard_type(v6, int)
guard_not_less_than(v6, 1)
v16 = dict_get(v2, "n")
guard_type(v16, int)
v21 = int_sub(v16, 1)
... (inlined) ...
finish(v64)
```

How to Reduce the RPython's Compilation Time

Issue: how to reduce compilation time in RPython

- Optimization / Code gen.
- Tracing
  - RPython traces recursions
- Recompilation at guard failing

How to Reduce the RPython's Compilation Time

Issue: how to reduce compilation time in RPython

Optimization / Code gen.

↑

Lightweight compilation

Tracing

RPython traces recursions

↑

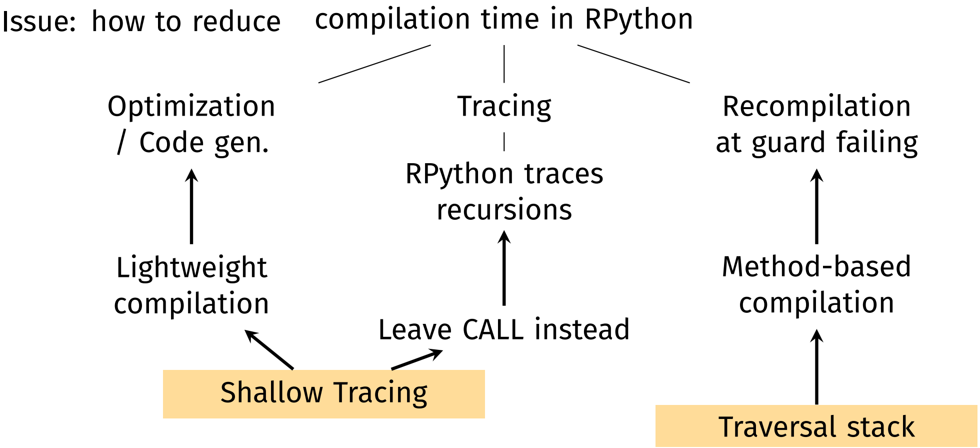
Leave CALL instead

Recompilation at guard failing

↑

Method-based compilation

How to Reduce the RPython's Compilation Time



Shallow Tracing Leaves CALLs and Doesn't Exec. Bodies

- `@dont_look_inside`: leaves a call to the decorated fun at tracing
  - but executes the body at tracing
- `if dummy: return`: skips executing the body during tracing
  - `dummy` turns into `False` after tracing

```
while True:
  instr = bytecode[pc++]
  if instr == INC:
    handler_INC(stack)
  elif instr == CALL:
    handler_CALL(stack)
  elif ...
    ...
    ...
```

```
@dont_look_inside
def handler_INC(stack,dummy=True):
  if dummy: return
  x = stack[sp--]
  z = add(x, 1)
  stack[sp++] = z

@dont_look_inside
def handler_CALL(stack,dummy=True):
  if dummy: return
  r = interp(stack, ..)
  push(r, stack)
```

```
# INC
call(handler_INC, ..)
# CALL
call(handler_CALL, ..)
...
```

Shallow Tracing is Implemented as Decorator

- `@dont_look_inside`: leaves a call to the decorated fun at tracing
  - but executes the body at tracing
- `if dummy: return`: skips executing the body during tracing
  - `dummy` turns into `False` after tracing

```
while True:
  instr = bytecode[pc++]
  if instr == INC:
    handler_INC(stack)
  elif instr == CALL:
    handler_CALL(stack)
  elif ...
    ...
    ...
```

```
@enable_shallow_tracing
def handler_INC(stack):

    x = stack[sp--]
    z = add(x, 1)
    stack[sp++] = z

@enable_shallow_tracing
def handler_CALL(stack):

    r = interp(stack, ..)
    push(r)
```

```
# INC
call(handler_INC, ..)
# CALL
call(handler_CALL, ..)
...
```

Realize Next Level by One Step "Deeper" Shallow Tracing

- Fold stack manipulations in shallow tracing

```
while True:
  instr = bytecode[pc++]
  if instr == INC:
    handler_INC(stack)
  elif instr == CALL:
    handler_CALL(stack)
  elif ...
    ...
    ...
```

```
def handler_INC(stack):

  x = stack[sp--]
  z = add(x, 1)
  stack[sp++] = z

@enable_shallow_tracing
def add(x, y):

  return x + y
```

```
L0:
  x1 = stack[sp--]
  z2 = add(x1, 1)
  stack[sp++] = z2
  guard_true(..)
  x3 = stack[sp--]
  z4 = add(x3, 1)
  stack[sp++] = z4
  jump(L0)
L1:
  ...
  finish(..)
```

Realize Next Level by One Step "Deeper" Shallow Tracing

- Fold stack manipulations in shallow tracing

```
while True:
  instr = bytecode[pc++]
  if instr == INC:
    handler_INC(stack)
  elif instr == CALL:
    handler_CALL(stack)
  elif ...
    ...
    ...
```

```
def handler_INC(stack):

  x = stack[sp--]
  z = add(x, 1)
  stack[sp++] = z

@enable_shallow_tracing
def add(x, y):

  return x + y
```

```
L0:
  x1 = stack[sp--]
  z2 = add(x1, 1)
  stack[sp++] = z2
  guard_true(..)
  x3 = stack[sp--]
  z4 = add(z2, 1)
  stack[sp++] = z4
  jump(L0)
L1:
  ...
  finish(..)
```