Optimization

NI(E)-GEN, Spring 2023

https://courses.fit.cvut.cz/NI-GEN

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FIT

Why?

- minimize overheads of the execution process (calls, jumps, etc.)
- minimize code size (beter Icache locality, smaller code size?)
- cache already computed values where possible (faster, smaller code)
- rewrite common sequences into more performant variants
- parallelization

What For?

- speed – the go-to variant
- size – where program size is a constraint (embedded)
- energy efficiency – very desired but next to impossible to quantify

Why not?

- Slow is Good
  - optimizations often include the side-channel attack surface
  - code can be deliberately made slow (even randomly slow) to prevent those

- Slow is Predictable
  - Instruction latencies can be used as explicit timing method (embedded)

- Slow is Robust
  - Compilers often include extra checks, asserts, or memory hints in non-optimized code for easier debugging

Why not?

- Debugging
  - Code layout means some breakpoints will not work
  - Optimized values mean limited introspection
  - Inlining changes stack layout
  - Advanced optimizations make the code look absolutely cryptic

- Compiler Errors
  - Sadly, optimizations are known to introduce subtle bugs
  - Turning them off for problematic parts of code often results in correct compilation

Basic Concepts

- Analysis
  - Passes that do not change the code, but gather semantic information about it
- Optimizations
  - Code changing passes, may invalidate optimizations
- Normalization
  - Often optimizations are done for “no good reason”, but they make the code more regular which in turns makes rest of the process easier
- Undefined Behavior
  - makes compiler happy – exact semantics does not have to be observed in undefined behavior situations, which allows for more optimization opportunities

Data-flow Optimizations

- Common Subexpression Elimination (CSE)
  - Reuses previously calculated identical values
- Global Value Numbering (GVN)
  - SSA-based version of CSE
- Strength Reduction
  - Replaces costly operations with identical but less expensive ones

Data-flow Optimizations

- Constant Folding & Propagation
  - Replaces variables with constants
- Bounds Check Elimination
  - Removes automatic bounds checking where possible

Code Removal

- Dead Instruction Elimination (DIE)
  - Removes instruction w/o sideeffects and no uses
- Dead Store Elimination (DSE)
  - Removes store of a never-read value (language dependent)
- Dead Code Elimination (DCE)
  - Removes unreachable code blocks

Function Call Optimizations

- Inlining – extremely useful
  - Removes function call overhead
  - But often more importantly increases the optimizer’s context

- Tail Call Optimization
  - requirement for functional languages

Loop Optimizations

- most execution time spent in loops, which makes loop optimizations the most important
- main themes are removal of loop overhead via various transformations (relatively easy)
- and enabling parallelism (very hard)

Loop Optimizations

- Loop unrolling
  - Reduces loop overhead by lowering loop iterations by copying its body

- Loop Inversion
  - Replaces while loop with guard and do-while

- Loop Interchange
  - Swaps nested loops for better cache locality

Loop Optimizations

- Loop Splitting & Peeling
  - single loop split into multiple loops iterating over disjoint contiguous areas of the previous range
  - improves cache locality, highlights potential parallelism
- Loop Unswitching
  - conditionals in the loop that will be the same for the whole loop are moved out of the loop and the rest of the loop is duplicated
- Loop Reversal
  - reverse the order of the loop. This does not change performance of the program, but rather enables other opimizations by potentially reducing dependencies

Loop Optimizations

- Loop Fission
  - breaks loop into multiple loops with distinct bodies (helps reference locality for the smaller bodies)
- Loop Fusion
  - combine multiple loops iterating the same amount of times / over same data as long as they do not reference each other
- Loop Invariant Code Motion
  - code that does not rely on the induction variable can be scheduled before the loop
  - this is only true if the loop is executed at least once, i.e. ideal for do-whole loops.

Speculative Optimizations

- not much used in ahead-of-time compilers
- extremely important for JITs and dynamic languages

- devirtualization
- non-null assumption
- type assumption
- value assumption

Partial Evaluation

```
int add(int i, int j) {
    return i + j;
}

int y = 0;
for (int x = 0; x < VERY_LARGE_N; ++x)
    y += add(1, x);
```

Partial Evaluation

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Partial Evaluation

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    y += add(x, 1);
```

Partial Evaluation

```
int add(int i, int j) {
    return i + j;
}

int y = 0;
λ inc = add(1);
for (int x = 0; x < VERY_LARGE_N; ++x)
    y += inc(x);
```

Partial Evaluation

```
#include <functional>
using namespace std::placeholders;

int add(int i, int j) {
    return i + j;
}

int y = 0;
auto inc = std::bind(add, 1, _2);
for (int x = 0; x < VERY_LARGE_N; ++x)
    y += inc(x);
```

Partial Evaluation

- generalization of the optimization by specialization
- creates new version of the function where some of its arguments are bound to constants, while others remain
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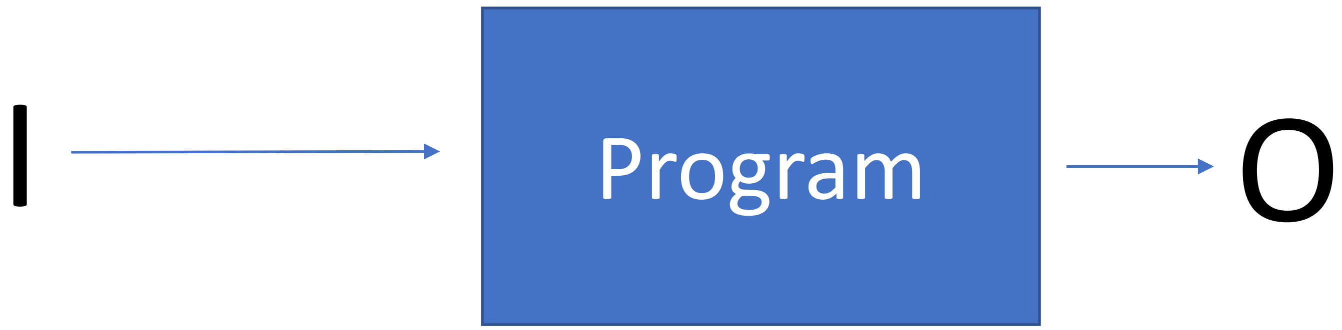
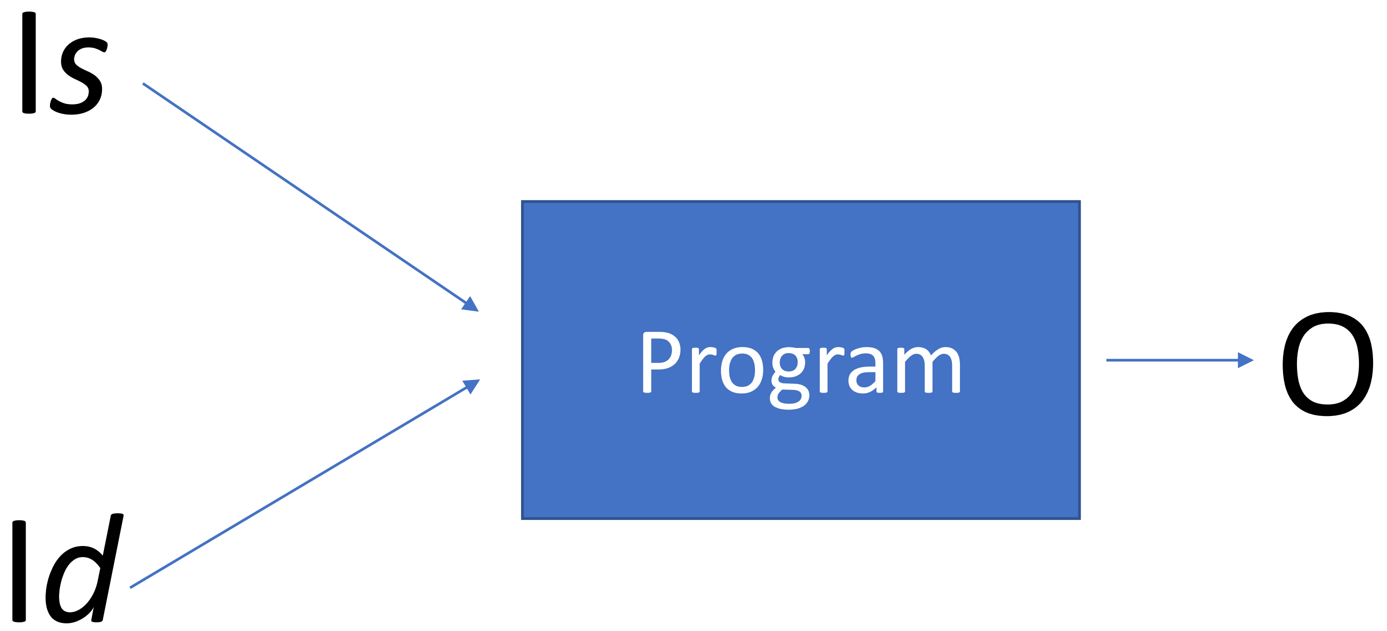
- creates new version of the function where some of its arguments are bound to constants, while others remain
- this increases the context for the optimizer in the specialized version
- can be generalized further to whole programs

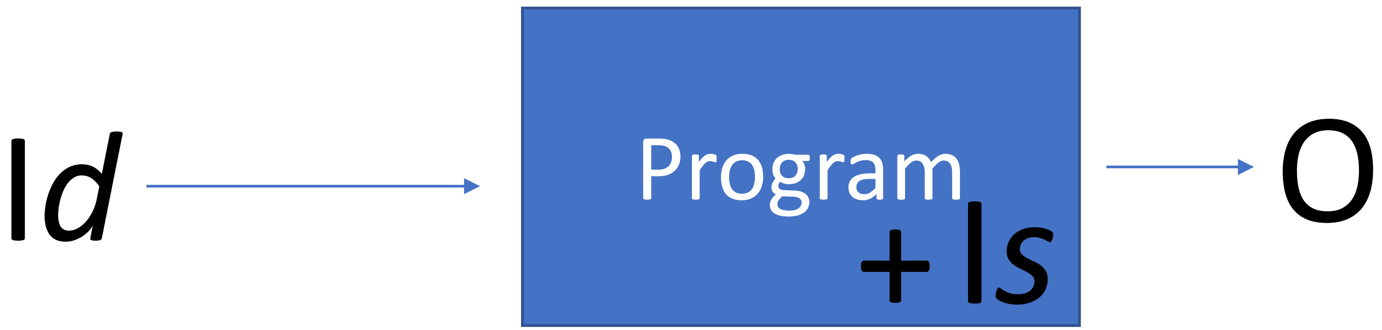
Partial Evaluation



Partial Evaluation



Partial Evaluation



Futamura Projections

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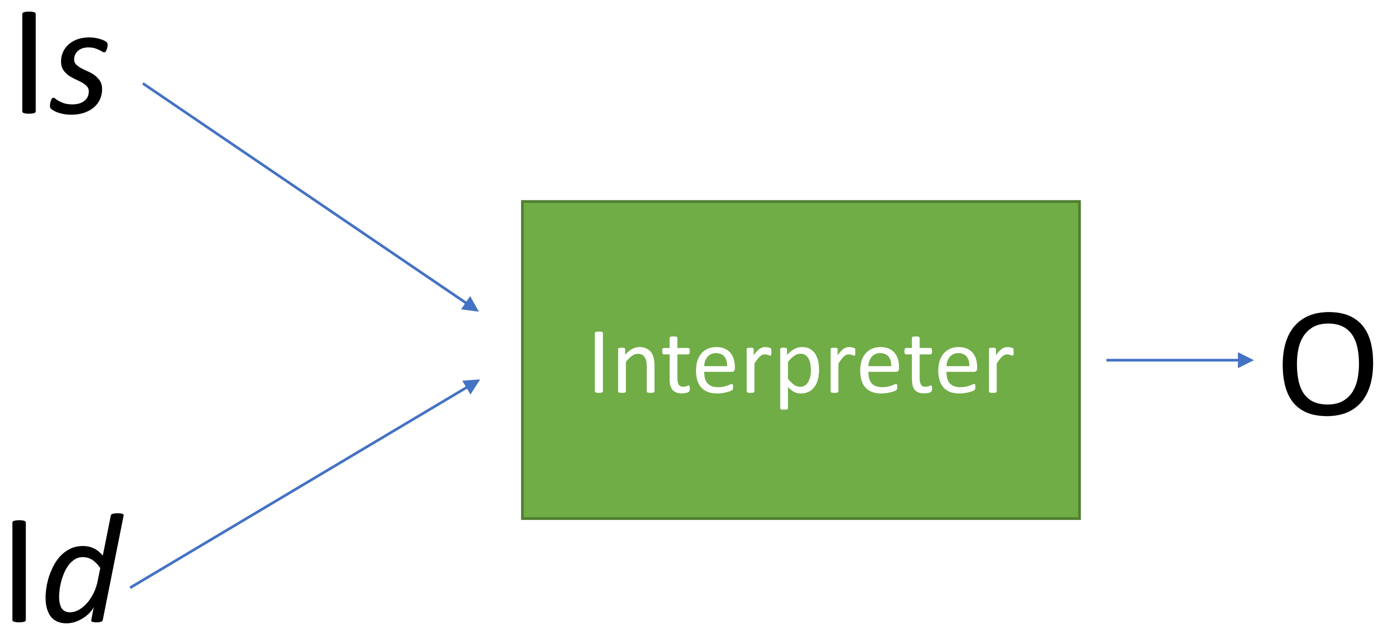

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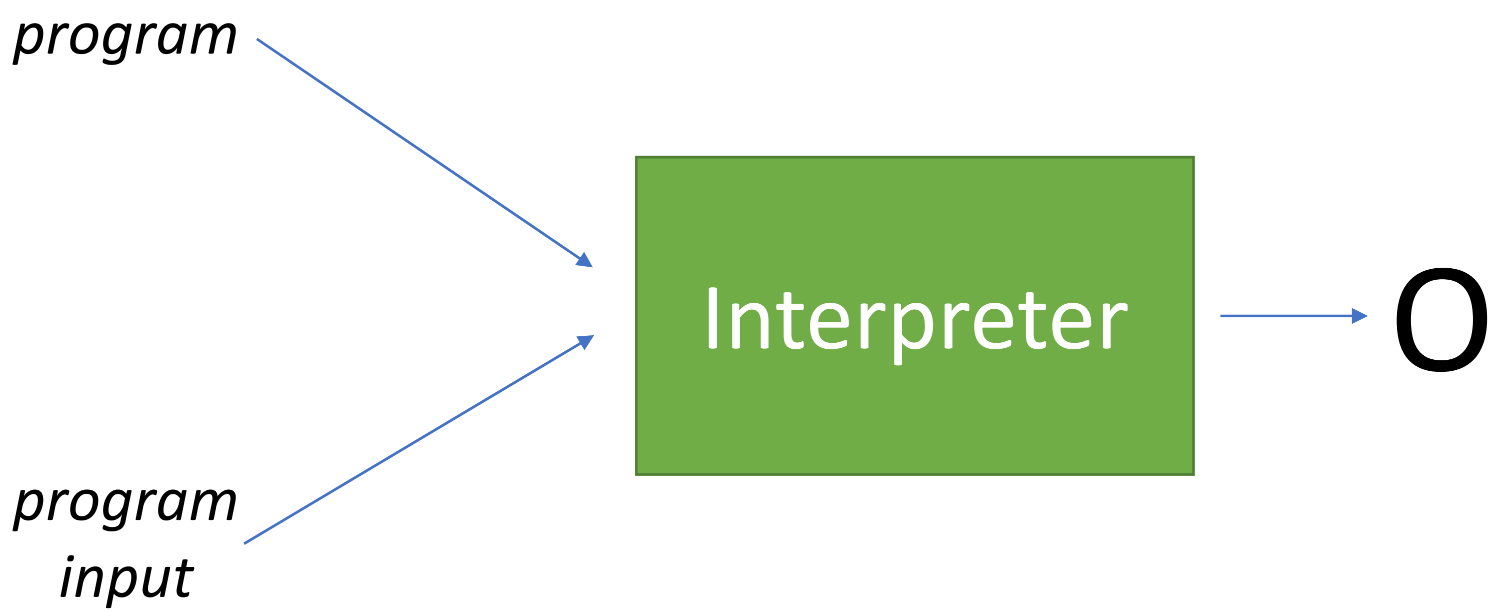

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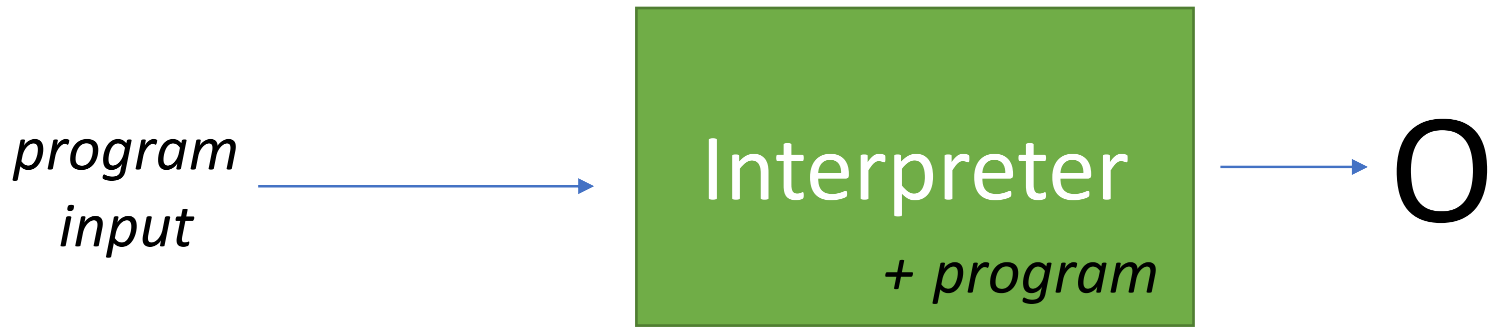

Futamura Projections

Futamura Projections (2)

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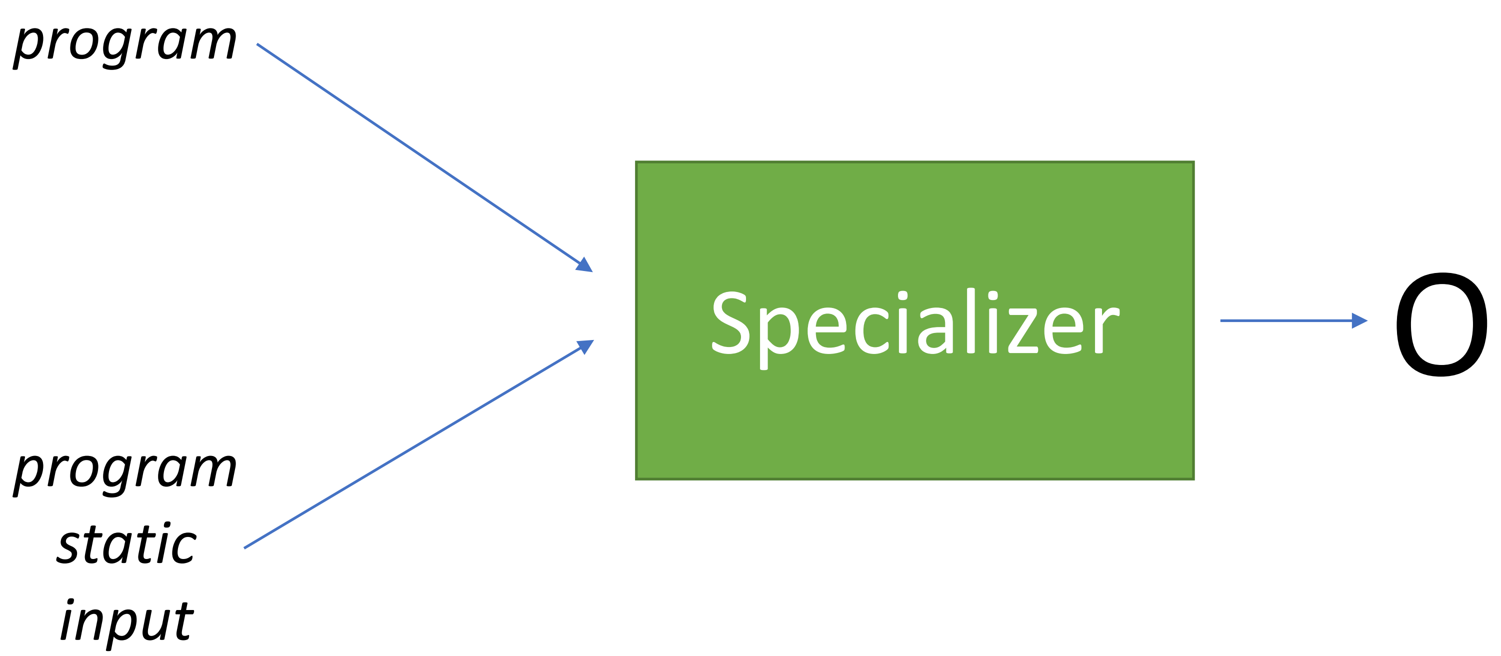

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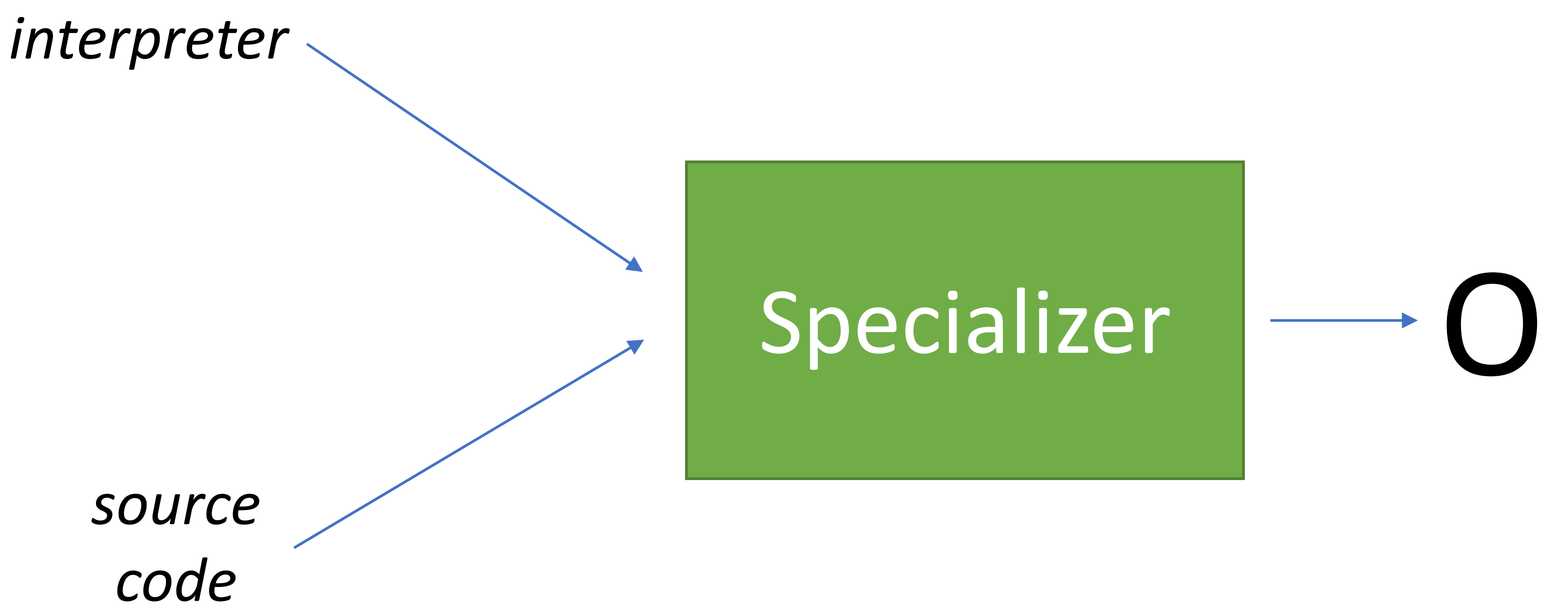

Futamura Projections (2)

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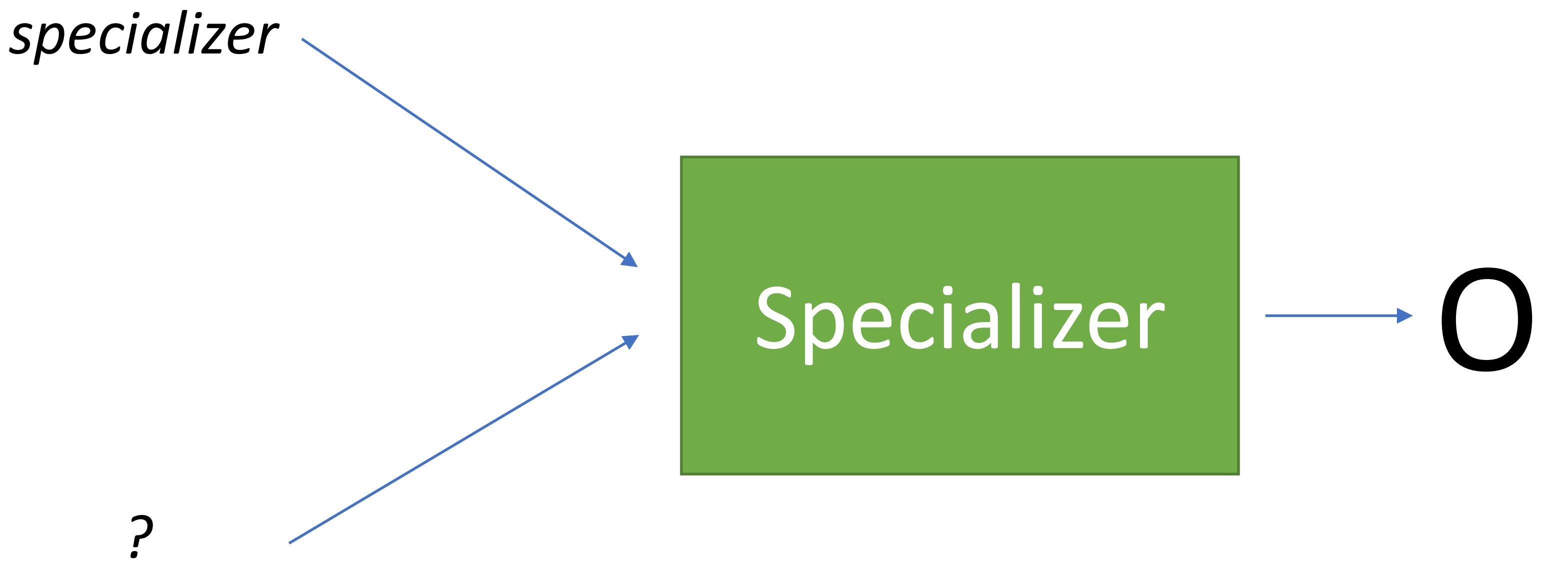
Futamura Projections (3)



Futamura Projections

I) specializing interpreter to source code yields executable

II) specializing specializer for an interpreter (as used in I) yields a compiler

III) specializing specialier for itself (as used in II) yields compiler generator that given an interpreter produces a compiler

Bootstrapping a compiler

- a compiler is bootstrapped (self-hosted) when it can compile itself
- increases confidence in the compiler
- allows for greater control of the compilation and optimization process
- requires the first version of the compiler to be written in a different language
- is a costly process