Regularizing Python using Structured Control Flow

Valentin Haenel

Senior Software Engineer - Open Source / Numba
https://anaconda.com

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Version: 2.0 https://github.com/esc/numba-scfg-talk

Outline

1. Prologue
2. Pipeline
3. Examples
   - Branch
   - Multi Return
   - While Loop
   - Early Exit
   - For Loop
   - Break and Continue
4. Epilogue

whoami

- Val Haenel ("val" like `let val` =)
- https://github.com/esc
- Compiler Engineer at Anaconda
- Working full-time on Numba
  - (the function compiler for numerical Python)
- Doing this for over 5 years

Introduction

- Using a Structured Control Flow Graph (SCFG)
- Regularize Python, identify branches and loops
- Branch and loop regions are closed and clearly identified
- Algorithm based on Bahmann2015
- Implemented in package numba-scfg
- Two main contributions:
  - → Application of an academic paper to Python source
  - → Solution to de-sugaring Python for-loops

Motivation

- Make code more amenable for Python compilers
- First step towards an source frontend for Numba
- (Numba currently uses bytecode...)

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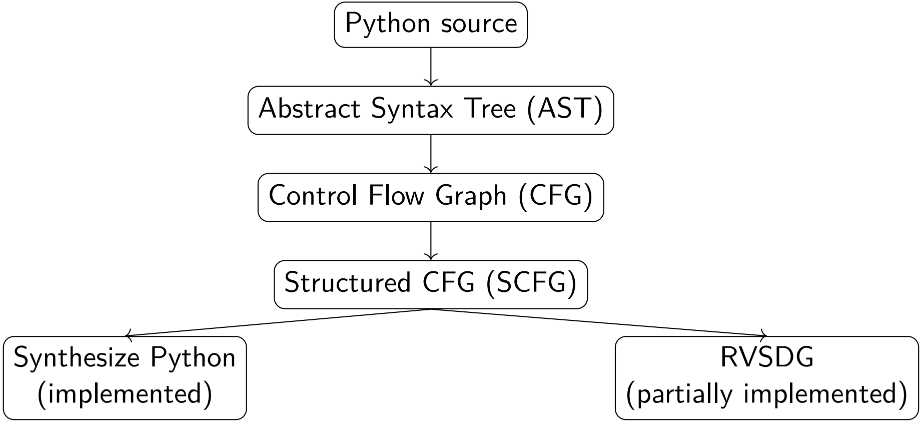
Pipeline



Python source

Abstract Syntax Tree (AST)

Control Flow Graph (CFG)

Structured CFG (SCFG)

Synthesize Python
(implemented)

RVSDG
(partially implemented)

CFG → SCFG

- Identifies loop and branch regions
- Loops become closed and tail controlled (do-while) with a single backedge
- Branch regions are identified as a structure of
  - one head region
  - two or more branch regions
  - one tail region

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Branch

- A simple example

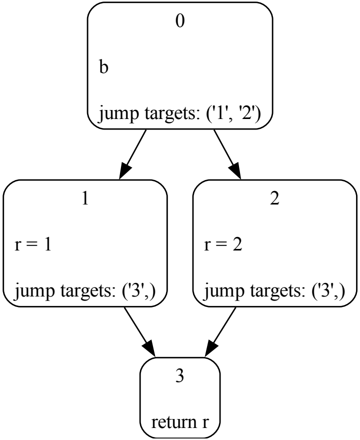
```python
def branch(b: int) -> int:
    if b:
        r = 1
    else:
        r = 2
    return r
```

AST

```
FunctionDef(
    name='branch',
    args=arguments(
        posonlyargs=[],
        args=[
            arg(
                arg='b',
                annotation=Name(id='int', ctx=Load()))],
        kwonlyargs=[],
        kw_defaults=[],
        defaults=[]),
    body=[
        If(
            test=Name(id='b', ctx=Load()),
            body=[
                Assign(
                    targets=[
                        Name(id='r', ctx=Store())],
                    value=Constant(value=1))],
            orelse=[
                Assign(
                    targets=[
                        Name(id='r', ctx=Store())],
                    value=Constant(value=2))]),
        Return(
            value=Name(id='r', ctx=Load()))],
    decorator_list=[],
    returns=Name(id='int', ctx=Load()),
    type_params=[])],
```

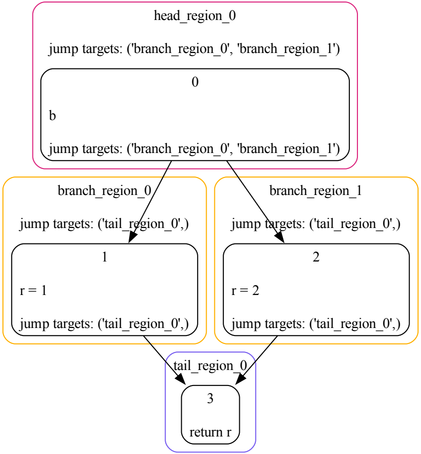
CFG

- CFG is already closed



SCFG

- Branch regions are identified, no "restructuring required"


head_region_0
jump targets: ('branch_region_0', 'branch_region_1')
0
b
jump targets: ('branch_region_0', 'branch_region_1')
branch_region_0
jump targets: ('tail_region_0',)
1
r = 1
jump targets: ('tail_region_0',)
branch_region_1
jump targets: ('tail_region_0',)
2
r = 2
jump targets: ('tail_region_0',)
tail_region_0
3
return r

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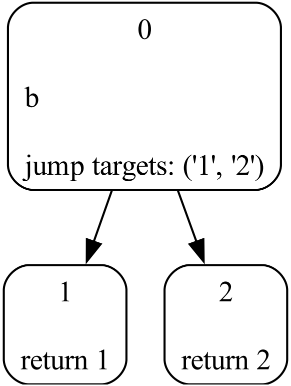
Multi Return

- This example has two `return` statements

```
def multi_return(b: int):
    if b:
        return 1
    else:
        return 2
```

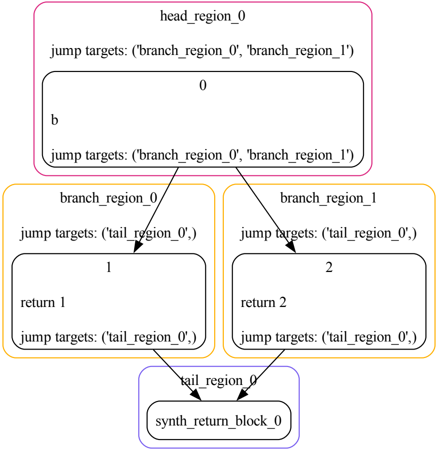
CFG

- The CFG is not closed, two exit nodes



SCFG

- The `CLOSE CFG` algorithm will restructure to insert an exit node



head_region_0
jump targets: ('branch_region_0', 'branch_region_1')
0
b
jump targets: ('branch_region_0', 'branch_region_1')
branch_region_0
jump targets: ('tail_region_0',)
1
return 1
jump targets: ('tail_region_0',)
branch_region_1
jump targets: ('tail_region_0',)
2
return 2
jump targets: ('tail_region_0',)
tail_region_0
synth_return_block_0

Transformed

- Finally, we can synthesize Python
- The transformed function only has a single `return`
- It is now closed

```
def transformed_multi_return(b: int):
    if b:
        __scfg_return_value__ = 1
    else:
        __scfg_return_value__ = 2
    return __scfg_return_value__
```

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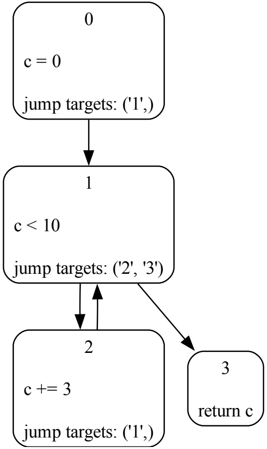
While Loop

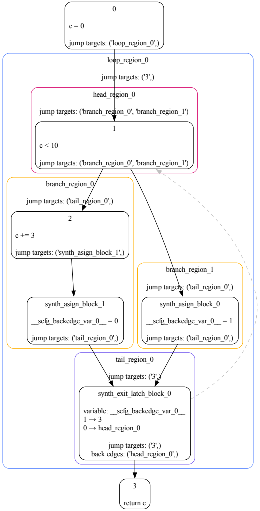
- Next up: a simple loop
- Remember: Loops are closed and tail controlled (do-while) with a single backedge

```python
def while_loop() -> int:
    c = 0
    while c < 10:
        c += 3
    return c
```

CFG


0
c = 0
jump targets: ('1',)
1
c < 10
jump targets: ('2', '3')
2
c += 3
jump targets: ('1',)
3
return c

SCFG



0

c = 0

jump targets: ('loop_region_0',)

loop_region_0

jump targets: ('3',)

head_region_0

jump targets: ('branch_region_0', 'branch_region_1')

1

c < 10

jump targets: ('branch_region_0', 'branch_region_1')

branch_region_0

jump targets: ('tail_region_0',)

2

c += 3

jump targets: ('synth_asign_block_1',)

synth_asign_block_1

__scfg_backedge_var_0__ = 0

jump targets: ('tail_region_0',)

branch_region_1

jump targets: ('tail_region_0',)

synth_asign_block_0

__scfg_backedge_var_0__ = 1

jump targets: ('tail_region_0',)

tail_region_0

jump targets: ('3',)

synth_exit_latch_block_0

variable: __scfg_backedge_var_0__
1 → 3
0 → head_region_0

jump targets: ('3',)
back edges: ('head_region_0',)

3

return c

Transformed

- The transformed variant is as close to a do-while loop as we can get in Python

```python
def transformed_while_loop() -> int:
    c = 0
    __scfg_loop_cont_1__ = True
    while __scfg_loop_cont_1__:
        if c < 10:
            c += 3
            __scfg_backedge_var_0__ = 0
        else:
            __scfg_backedge_var_0__ = 1
        __scfg_loop_cont_1__ = not __scfg_backedge_var_0__
    return c
```

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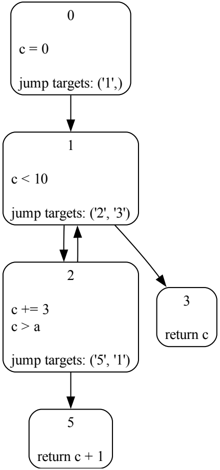
Early Exit

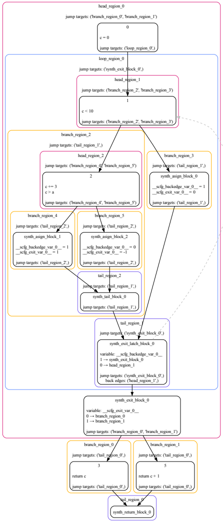
- Let's combine all three stages in this example
- The loop has an "early exit"
- This may be a problem for compilers, e.g, loop-unroll

```
def early_exit(a: int) -> int:
    c = 0
    while c < 10:
        c += 3
        if c > a:
            return c + 1
    return c
```

CFG


0
c = 0
jump targets: ('1',)
1
c < 10
jump targets: ('2', '3')
2
c += 3
c > a
jump targets: ('5', '1')
3
return c
5
return c + 1

SCFG


head_region_0
jump targets: ('branch_region_0', 'branch_region_1')
0
c = 0
jump targets: ('loop_region_0',)
loop_region_0
jump targets: ('synth_exit_block_0',)
head_region_1
jump targets: ('branch_region_2', 'branch_region_3')
1
c < 10
jump targets: ('branch_region_2', 'branch_region_3')
branch_region_2
jump targets: ('tail_region_1',)
head_region_2
jump targets: ('branch_region_4', 'branch_region_5')
2
c += 3
c > a
jump targets: ('branch_region_4', 'branch_region_5')
branch_region_3
jump targets: ('tail_region_1',)
synth_asign_block_0
__scfg_backedge_var_0__ = 1
__scfg_exit_var_0__ = 0
jump targets: ('tail_region_1',)
branch_region_4
jump targets: ('tail_region_2',)
synth_asign_block_1
__scfg_backedge_var_0__ = 1
__scfg_exit_var_0__ = 1
jump targets: ('tail_region_2',)
branch_region_5
jump targets: ('tail_region_2',)
synth_asign_block_2
__scfg_backedge_var_0__ = 0
__scfg_exit_var_0__ = -1
jump targets: ('tail_region_2',)
tail_region_2
jump targets: ('tail_region_1',)
synth_tail_block_0
jump targets: ('tail_region_1',)
tail_region_1
jump targets: ('synth_exit_block_0',)
synth_exit_latch_block_0
variable: __scfg_backedge_var_0__
1 → synth_exit_block_0
0 → head_region_1
jump targets: ('synth_exit_block_0',)
back edges: ('head_region_1',)
synth_exit_block_0
variable: __scfg_exit_var_0__
0 → branch_region_0
1 → branch_region_1
jump targets: ('branch_region_0', 'branch_region_1')
branch_region_0
jump targets: ('tail_region_0',)
3
return c
jump targets: ('tail_region_0',)
branch_region_1
jump targets: ('tail_region_0',)
5
return c + 1
jump targets: ('tail_region_0',)
tail_region_0
synth_return_block_0

Transformed

```python
def transformed_early_exit(a: int) -> int:
    c = 0
    __scfg_loop_cont_1__ = True
    while __scfg_loop_cont_1__:
        if c < 10:
            c += 3
            if c > a:
                __scfg_exit_var_0__ = 1
                __scfg_backedge_var_0__ = 1
            else:
                __scfg_backedge_var_0__ = 0
                __scfg_exit_var_0__ = -1
        else:
            __scfg_exit_var_0__ = 0
            __scfg_backedge_var_0__ = 1
        __scfg_loop_cont_1__ = not __scfg_backedge_var_0__
    if __scfg_exit_var_0__ in (0,):
        __scfg_return_value__ = c
    else:
        __scfg_return_value__ = c + 1
    return __scfg_return_value__
```

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For Loop

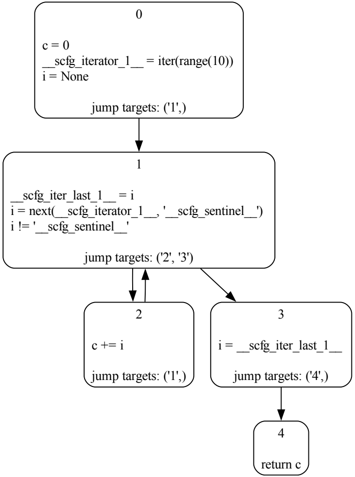
- Python for-loops need to be "de-sugared"
  - → such that they can be represented using the "blocks and edges" semantics of the CFG formalism

- Setup the induction variable
- Setup the iterator
- Use `next` to determine when to stop instead of catching the `StopIteration` exception
- The induction variable must escape the scope

```python
def for_loop() -> int:
    c = 0
    for i in range(10):
        c += i
    return c
```

CFG

- De-sugaring happens on-the-fly during conversion to CFG



0

```
c = 0
__scfg_iterator_1__ = iter(range(10))
i = None
```

jump targets: ('1',)

1

```
__scfg_iter_last_1__ = i
i = next(__scfg_iterator_1__, '__scfg_sentinel__')
i != '__scfg_sentinel__'
```

jump targets: ('2', '3')

2

```
c += i
```

jump targets: ('1',)

3

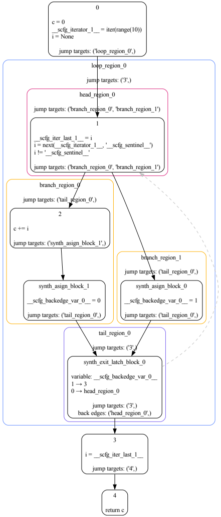
```
i = __scfg_iter_last_1__
```

jump targets: ('4',)

4

```
return c
```

SCFG



```
0

c = 0
__scfg_iterator_1__ = iter(range(10))
i = None

jump targets: ('loop_region_0',)

loop_region_0

jump targets: ('3',)

head_region_0

jump targets: ('branch_region_0', 'branch_region_1')

1

__scfg_iter_last_1__ = i
i = next(__scfg_iterator_1__, '__scfg_sentinel__')
i != '__scfg_sentinel__'

jump targets: ('branch_region_0', 'branch_region_1')

branch_region_0

jump targets: ('tail_region_0',)

2

c += i

jump targets: ('synth_asign_block_1',)

synth_asign_block_1

__scfg_backedge_var_0__ = 0

jump targets: ('tail_region_0',)

branch_region_1

jump targets: ('tail_region_0',)

synth_asign_block_0

__scfg_backedge_var_0__ = 1

jump targets: ('tail_region_0',)

tail_region_0

jump targets: ('3',)

synth_exit_latch_block_0

variable: __scfg_backedge_var_0__
1 → 3
0 → head_region_0

jump targets: ('3',)
back edges: ('head_region_0',)

3

i = __scfg_iter_last_1__

jump targets: ('4',)

4

return c
```

Transformed

```
def transformed_for_loop() -> int:
    c = 0
    __scfg_iterator_1__ = iter(range(10))
    i = None
    __scfg_loop_cont_1__ = True
    while __scfg_loop_cont_1__:
        __scfg_iter_last_1__ = i
        i = next(__scfg_iterator_1__, '__scfg_sentinel__')
        if i != '__scfg_sentinel__':
            c += i
            __scfg_backedge_var_0__ = 0
        else:
            __scfg_backedge_var_0__ = 1
        __scfg_loop_cont_1__ = not __scfg_backedge_var_0__
    i = __scfg_iter_last_1__
    return c
```

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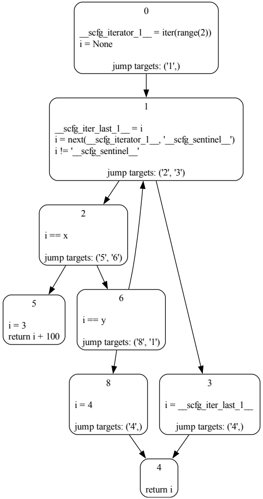
Break and Continue

- Both break and continue will be removed
    - (They are just syntactic sugar)

```python
def break_and_continue(x: int, y: int) -> int:
    for i in range(2):
        if i == x:
            i = 3
            return i + 100
        elif i == y:
            i = 4
            break
        else:
            continue
    return i
```

CFG



```
0

__scfg_iterator_1__ = iter(range(2))
i = None

jump targets: ('1',)
```

```
1

__scfg_iter_last_1__ = i
i = next(__scfg_iterator_1__, '__scfg_sentinel__')
i != '__scfg_sentinel__'

jump targets: ('2', '3')
```

```
2

i == x

jump targets: ('5', '6')
```

```
5

i = 3
return i + 100
```

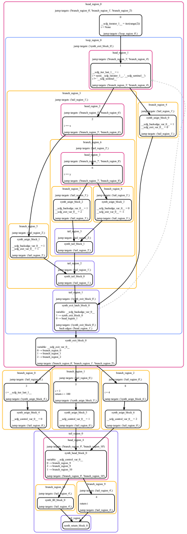
```
6

i == y

jump targets: ('8', '1')
```

```
8

i = 4

jump targets: ('4',)
```

```
3

i = __scfg_iter_last_1__

jump targets: ('4',)
```

```
4

return i
```

SCFG


head_region_0
jump targets: ('branch_region_0', 'branch_region_1', 'branch_region_2')
0
__scfg_iterator_1__ = iter(range(2))
i = None
jump targets: ('loop_region_0',)
loop_region_0
jump targets: ('synth_exit_block_0',)
head_region_1
jump targets: ('branch_region_3', 'branch_region_4')
1
__scfg_iter_last_1__ = i
i = next(__scfg_iterator_1__, '__scfg_sentinel__')
i != '__scfg_sentinel__'
jump targets: ('branch_region_3', 'branch_region_4')
branch_region_3
jump targets: ('tail_region_1',)
head_region_2
jump targets: ('branch_region_5', 'branch_region_6')
2
i == x
jump targets: ('branch_region_5', 'branch_region_6')
branch_region_4
jump targets: ('tail_region_1',)
synth_asign_block_0
__scfg_backedge_var_0__ = 1
__scfg_exit_var_0__ = 0
jump targets: ('tail_region_1',)
branch_region_6
jump targets: ('tail_region_2',)
head_region_3
jump targets: ('branch_region_7', 'branch_region_8')
6
i == y
jump targets: ('branch_region_7', 'branch_region_8')
branch_region_7
jump targets: ('tail_region_3',)
synth_asign_block_2
__scfg_backedge_var_0__ = 1
__scfg_exit_var_0__ = 2
jump targets: ('tail_region_3',)
branch_region_8
jump targets: ('tail_region_3',)
synth_asign_block_3
__scfg_backedge_var_0__ = 0
__scfg_exit_var_0__ = -1
jump targets: ('tail_region_3',)
branch_region_5
jump targets: ('tail_region_2',)
synth_asign_block_1
__scfg_backedge_var_0__ = 1
__scfg_exit_var_0__ = 1
jump targets: ('tail_region_2',)
tail_region_3
jump targets: ('tail_region_2',)
synth_tail_block_1
jump targets: ('tail_region_2',)
tail_region_2
jump targets: ('tail_region_1',)
synth_tail_block_0
jump targets: ('tail_region_1',)
tail_region_1
jump targets: ('synth_exit_block_0',)
synth_exit_latch_block_0
variable: __scfg_backedge_var_0__
1 → synth_exit_block_0
0 → head_region_1
jump targets: ('synth_exit_block_0',)
back edges: ('head_region_1',)
synth_exit_block_0
variable: __scfg_exit_var_0__
0 → branch_region_0
1 → branch_region_1
2 → branch_region_2
jump targets: ('branch_region_0', 'branch_region_1', 'branch_region_2')
branch_region_0
jump targets: ('tail_region_0',)
3
i = __scfg_iter_last_1__
jump targets: ('synth_asign_block_4',)
synth_asign_block_4
__scfg_control_var_0__ = 0
jump targets: ('tail_region_0',)
branch_region_1
jump targets: ('tail_region_0',)
5
i = 3
return i + 100
jump targets: ('synth_asign_block_5',)
synth_asign_block_5
__scfg_control_var_0__ = 1
jump targets: ('tail_region_0',)
branch_region_2
jump targets: ('tail_region_0',)
8
i = 4
jump targets: ('synth_asign_block_6',)
synth_asign_block_6
__scfg_control_var_0__ = 2
jump targets: ('tail_region_0',)
tail_region_0
head_region_4
jump targets: ('branch_region_9', 'branch_region_10')
synth_head_block_0
variable: __scfg_control_var_0__
0 → branch_region_9
2 → branch_region_9
1 → branch_region_10
jump targets: ('branch_region_9', 'branch_region_10')
branch_region_10
jump targets: ('tail_region_4',)
synth_fill_block_0
jump targets: ('tail_region_4',)
branch_region_9
jump targets: ('tail_region_4',)
4
return i
jump targets: ('tail_region_4',)
tail_region_4
synth_return_block_0

Transformed

```python
def transformed_break_and_continue(x: int, y: int) -> int:
    __scfg_iterator_1__ = iter(range(2))
    i = None
    __scfg_loop_cont_1__ = True
    while __scfg_loop_cont_1__:
        __scfg_iter_last_1__ = i
        i = next(__scfg_iterator_1__, '__scfg_sentinel__')
        if i != '__scfg_sentinel__':
            if i == x:
                __scfg_exit_var_0__ = 1
                __scfg_backedge_var_0__ = 1
            elif i == y:
                __scfg_exit_var_0__ = 2
                __scfg_backedge_var_0__ = 1
            else:
                __scfg_backedge_var_0__ = 0
                __scfg_exit_var_0__ = -1
        else:
            __scfg_exit_var_0__ = 0
            __scfg_backedge_var_0__ = 1
        __scfg_loop_cont_1__ = not __scfg_backedge_var_0__
```

Transformed

```
if __scfg_exit_var_0__ in (0,):
    i = __scfg_iter_last_1__
    __scfg_control_var_0__ = 0
elif __scfg_exit_var_0__ in (1,):
    i = 3
    __scfg_return_value__ = i + 100
    __scfg_control_var_0__ = 1
else:
    i = 4
    __scfg_control_var_0__ = 2
if __scfg_control_var_0__ in (0, 2):
    __scfg_return_value__ = i
else:
    pass
return __scfg_return_value__
```

Outline

1. Prologue
2. Pipeline
3. Examples
    - Branch
    - Multi Return
    - While Loop
    - Early Exit
    - For Loop
    - Break and Continue
4. Epilogue

Future Work

- Explore full transformation to RVSDG
- Implement Source/AST frontend for Numba
- Find other potential uses...

Conclusion

- Open source tools used to make this presentation:
  - Wiki2beamer
  - LaTeXbeamer
  - Dia
  - Pygments
  - Minted
  - Solarized theme for pygments

Questions?

- Questions?