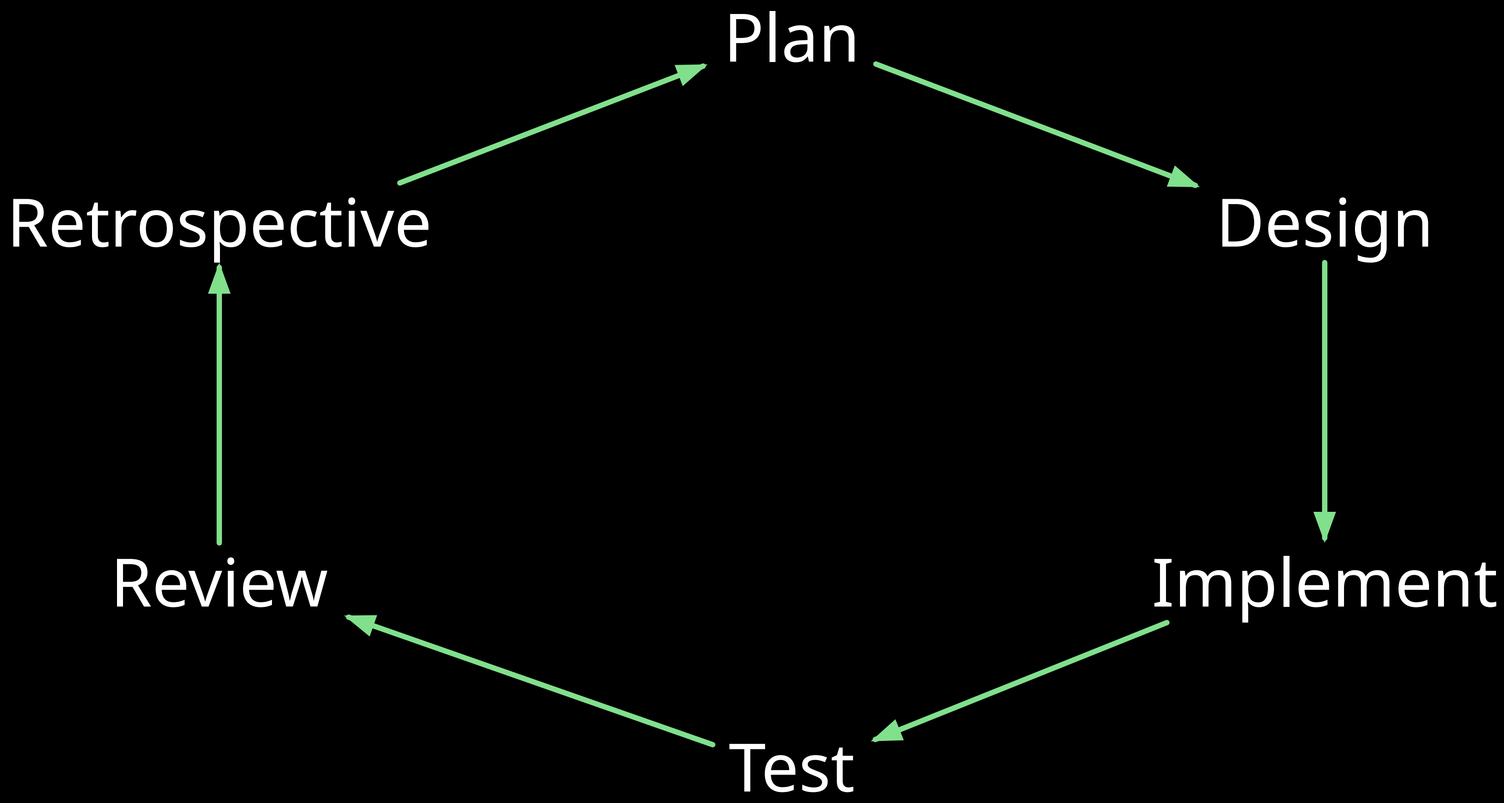
Spade, and Using Your Language in Agile Design

Frans Skarman

Hochschule München



Plan

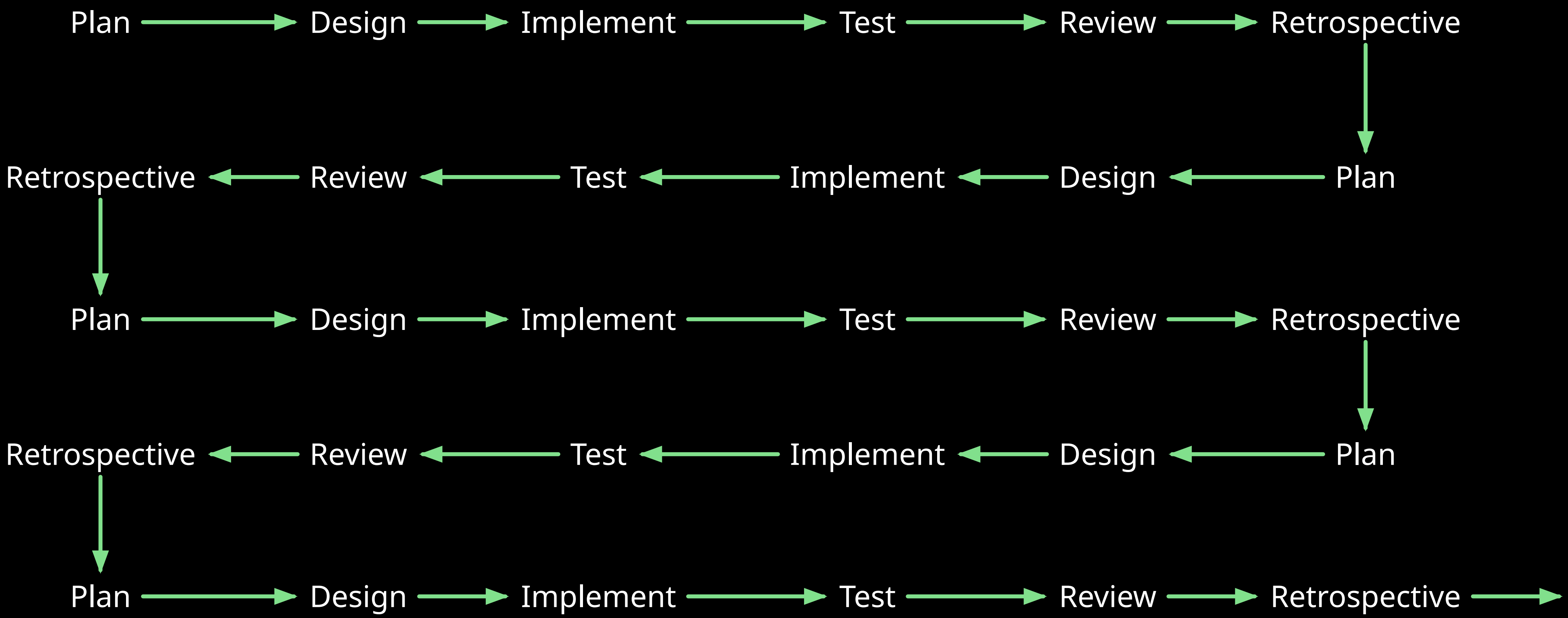
Design

Implement

Test

Review

Retrospective



Plan → Design → Implement → Test → Review → Retrospective

Retrospective ← Review ← Test ← Implement ← Design ← Plan

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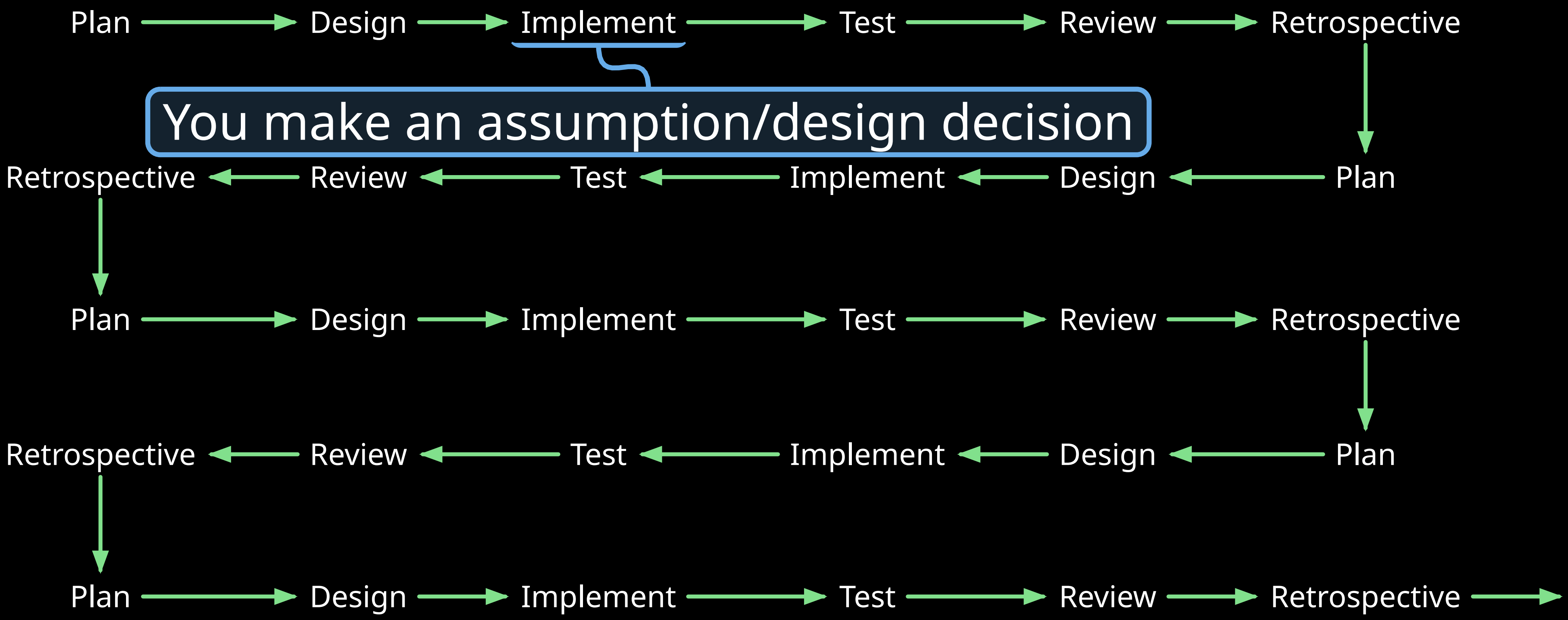

Plan → Design → Implement → Test → Review → Retrospective

You make an assumption/design decision

Retrospective ← Review ← Test ← Implement ← Design ← Plan

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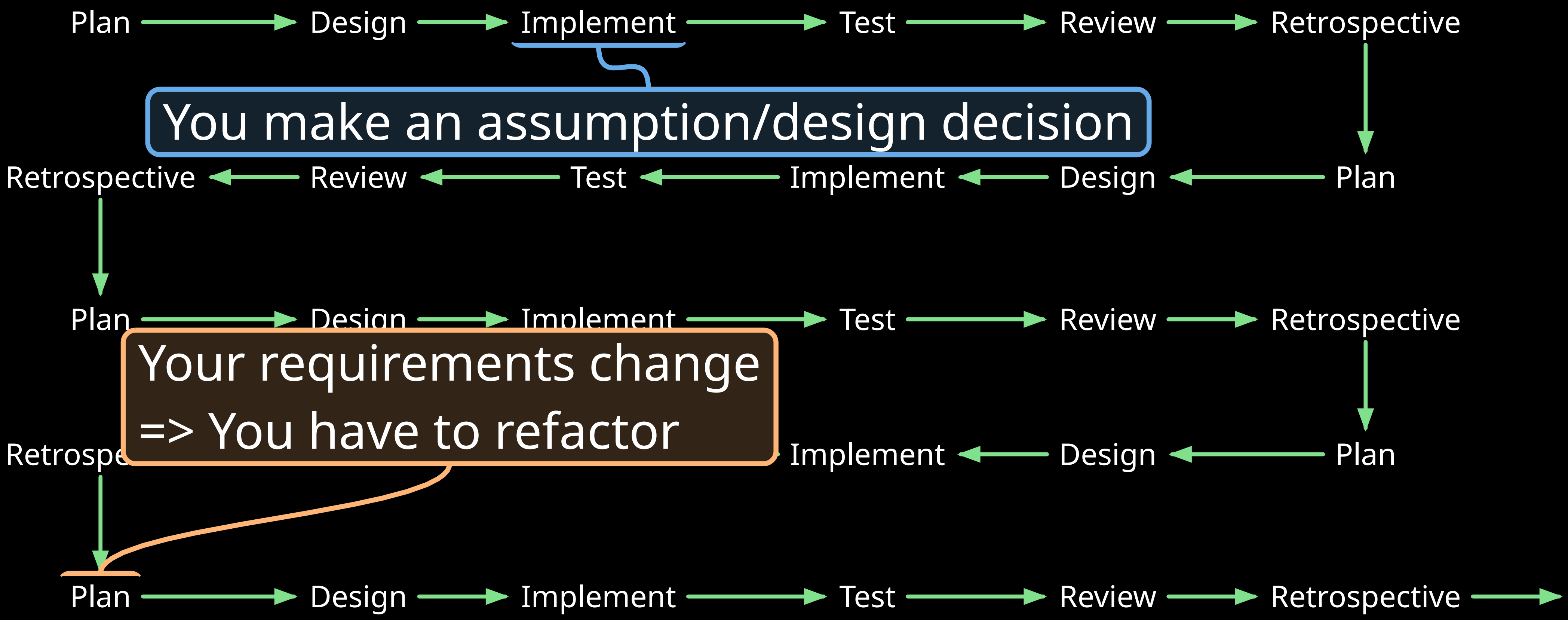

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You make an assumption/design decision

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Your requirements change
=> You have to refactor

Retrospe Implement ← Design ← Plan

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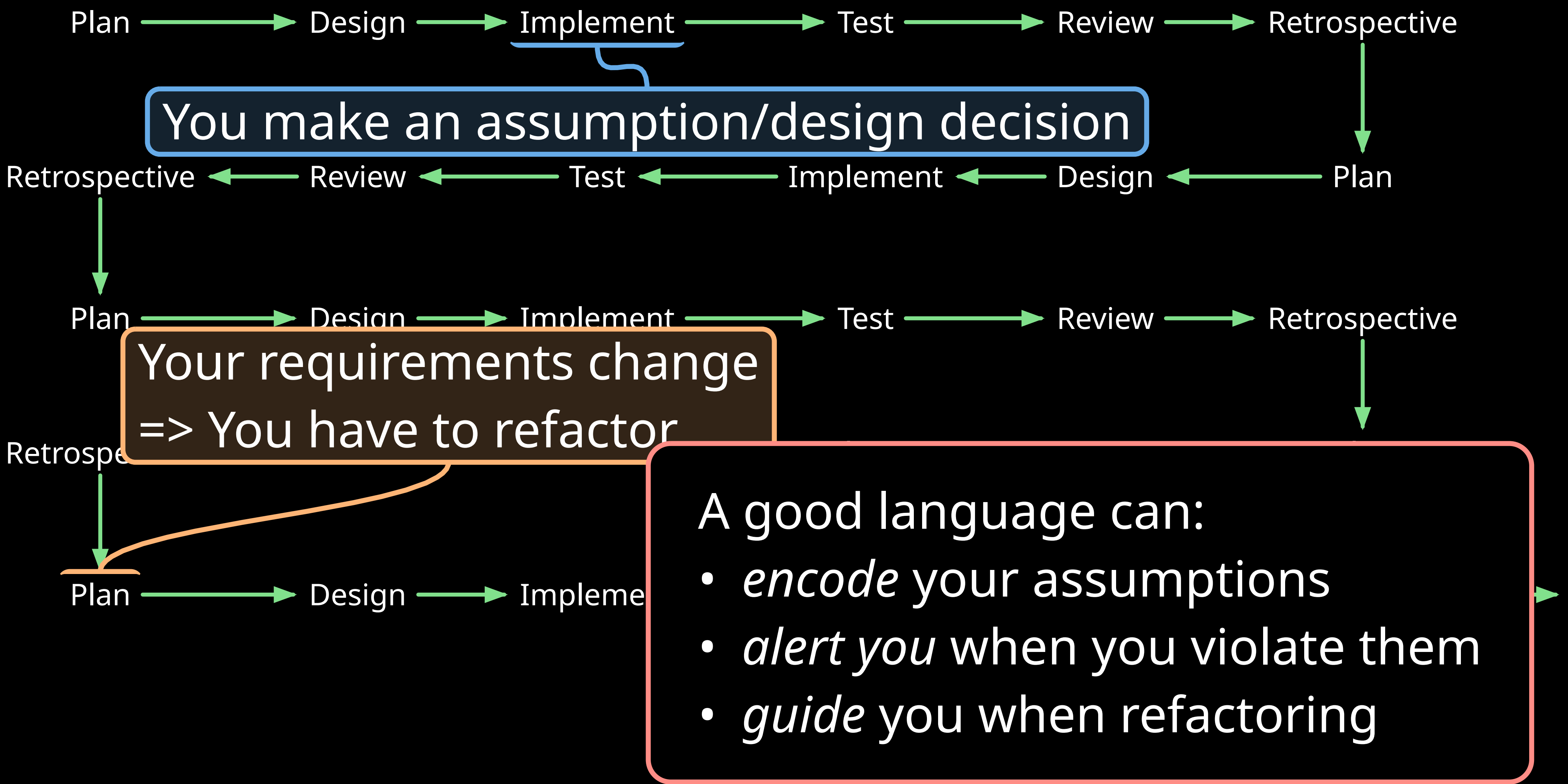
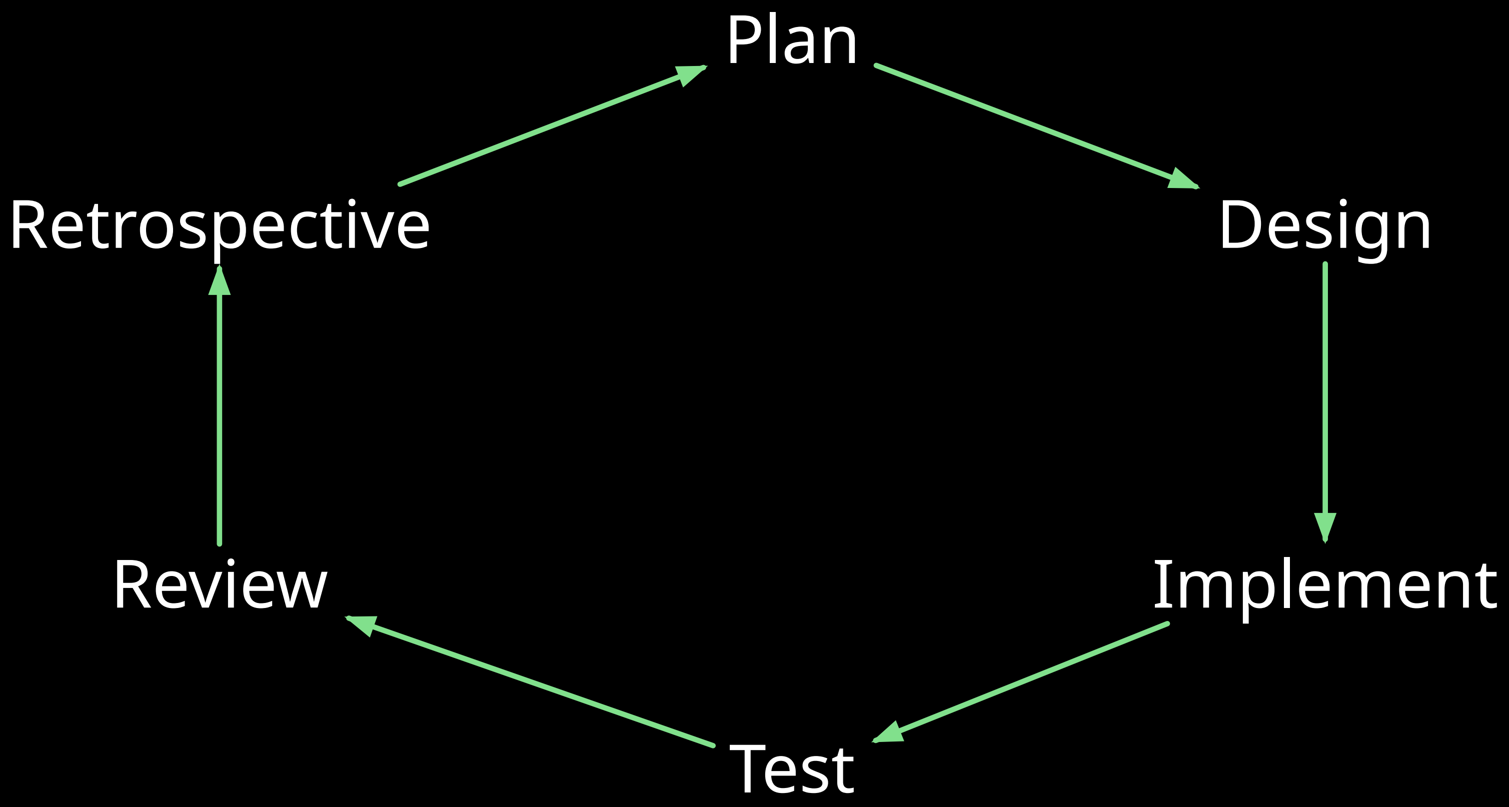


You make an assumption/design decision

Your requirements change
=> You have to refactor

A good language can:

- *encode* your assumptions
- *alert you* when you violate them
- *guide* you when refactoring



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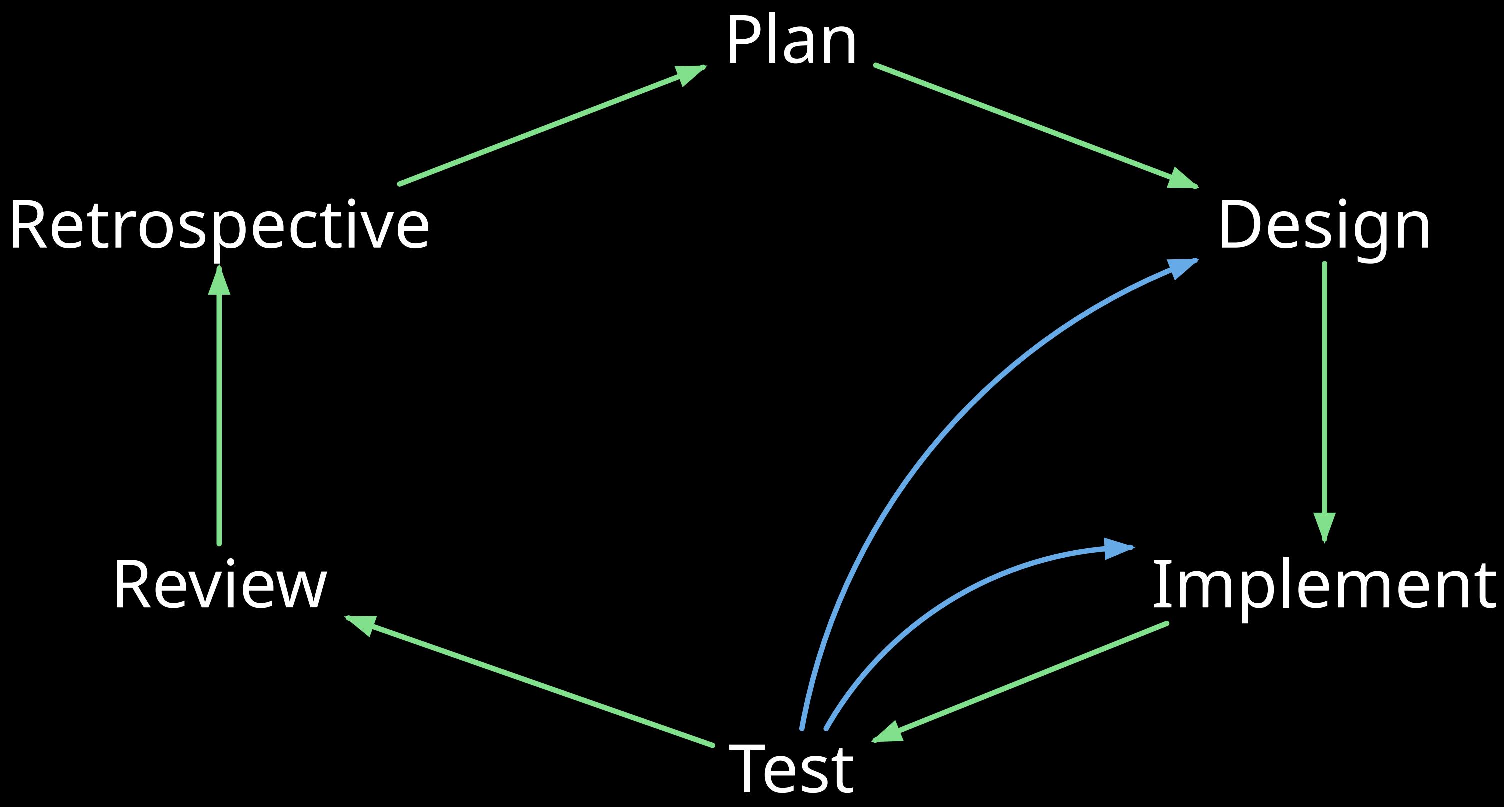

Plan

Retrospective

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Implement

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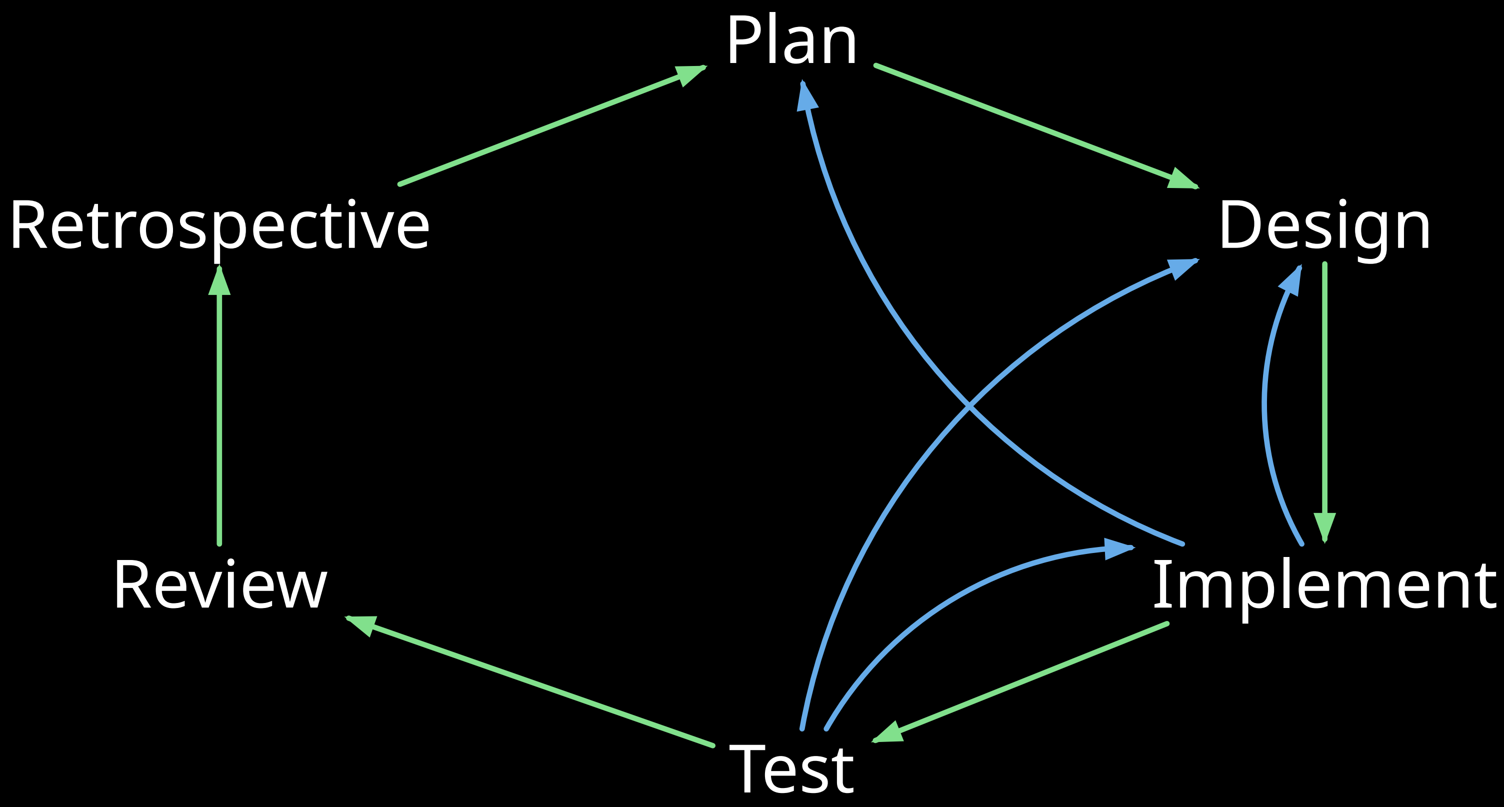

Plan

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Design

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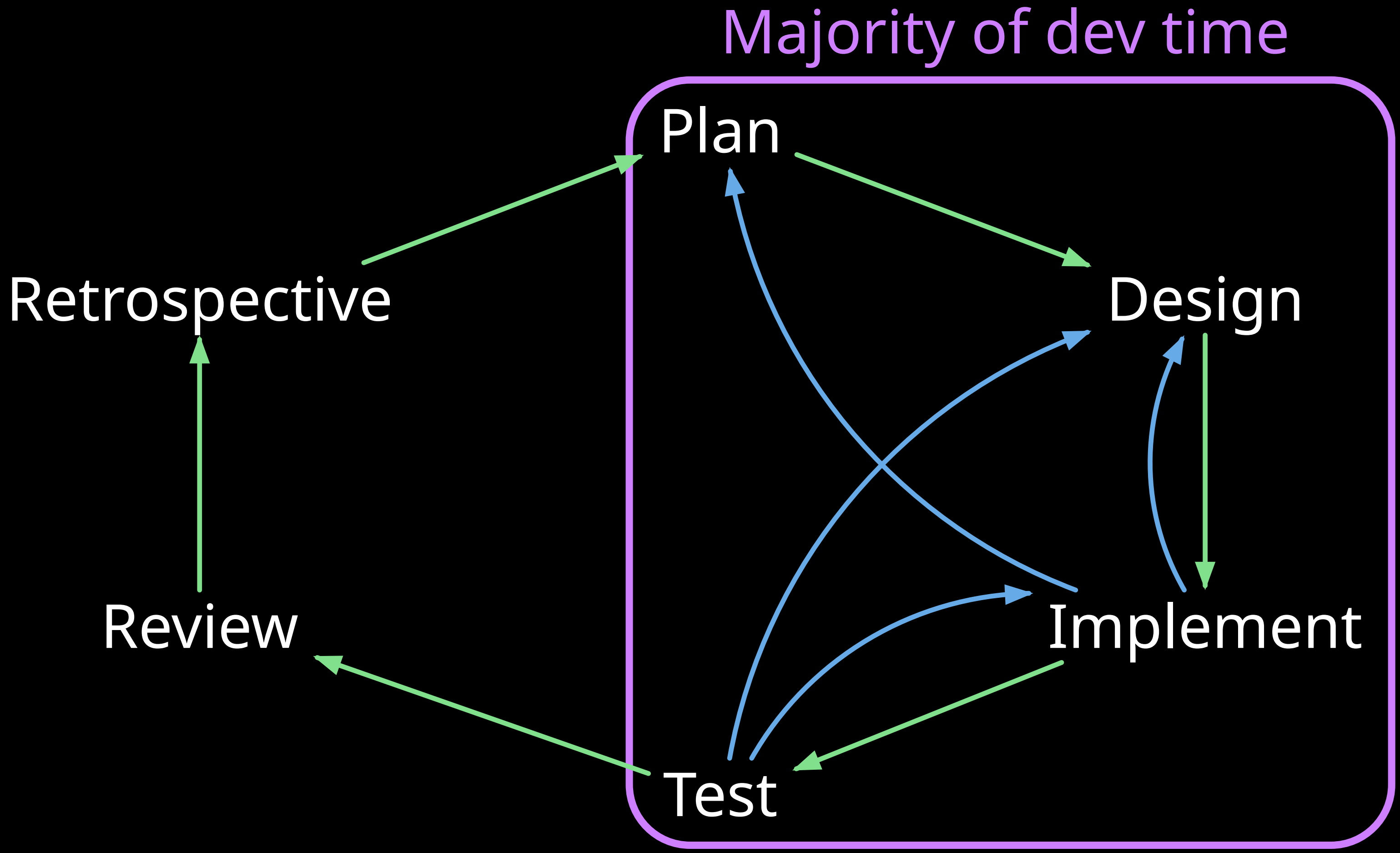
Majority of dev time
Plan
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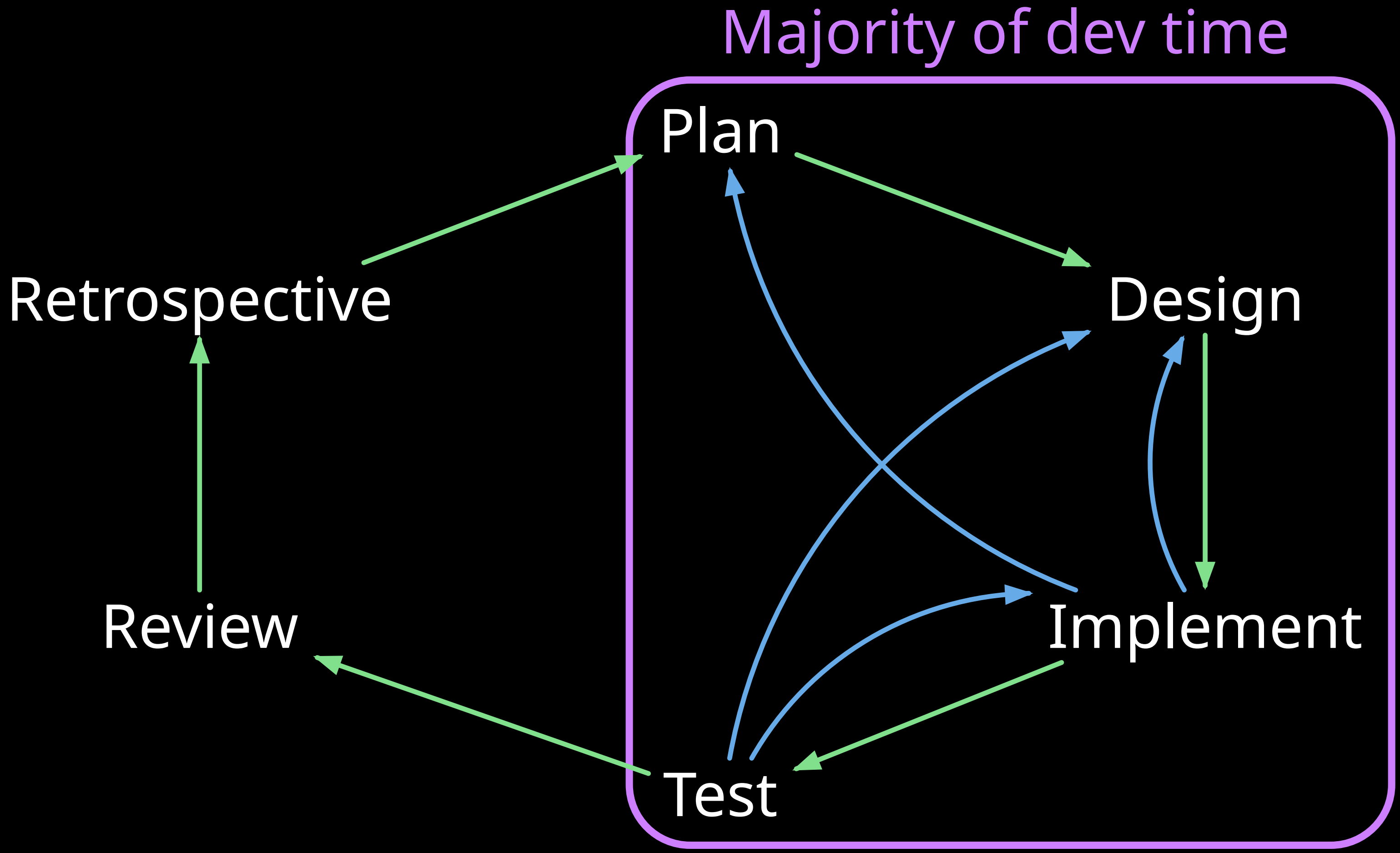
Retrospective



Majority of dev time

Plan

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Retrospective

- 0.1 second user feels that the system is **reacting instantaneously**

- Usability Engineering — Jakob Nielsen

- 0.1 second user feels that the system is **reacting instantaneously**
- 1.0 second flow of thought **stays uninterrupted**

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- 10 seconds is about the limit for **keeping the user’s attention**

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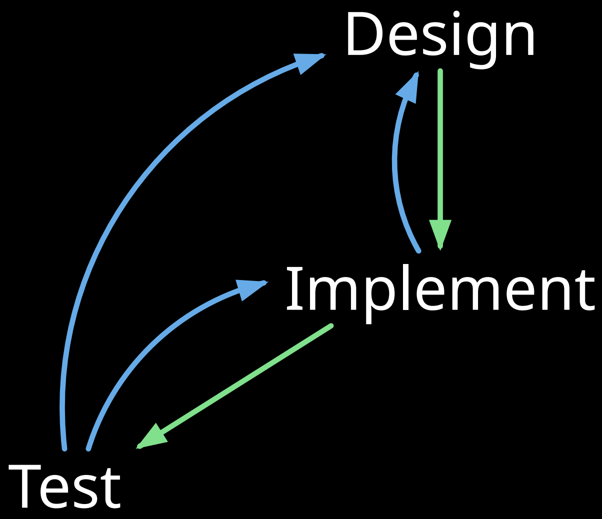

- Usability Engineering — Jakob Nielsen

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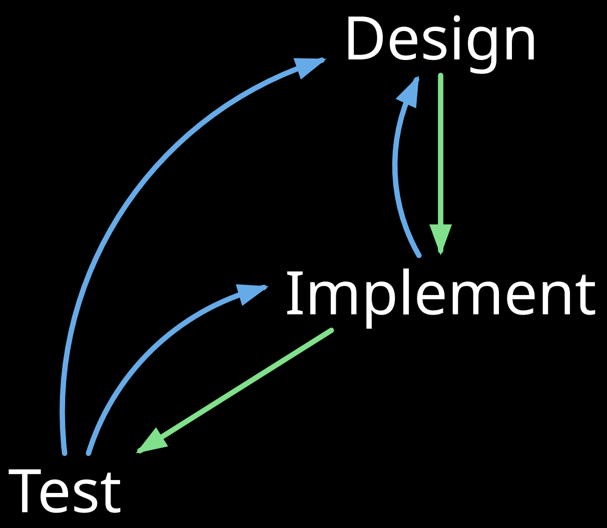
How long is your simulation runtime?



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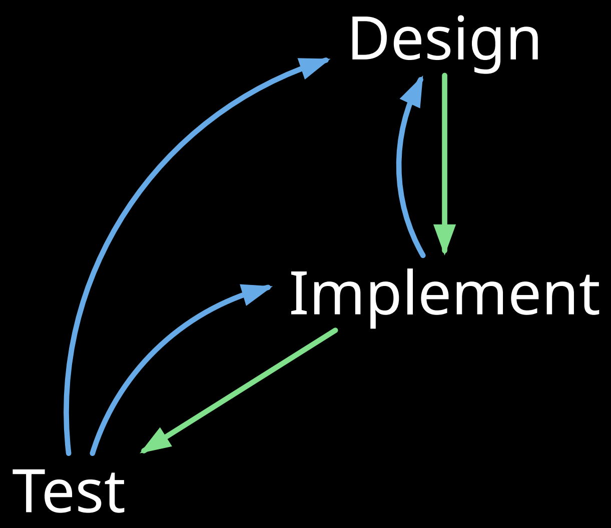
How long is your simulation runtime?

What about synthesis??



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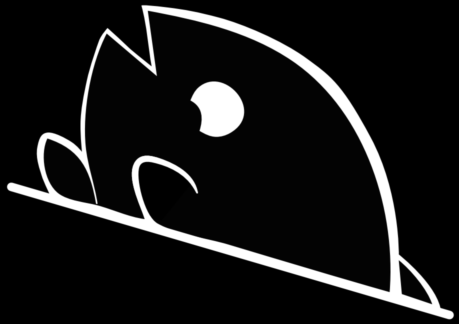
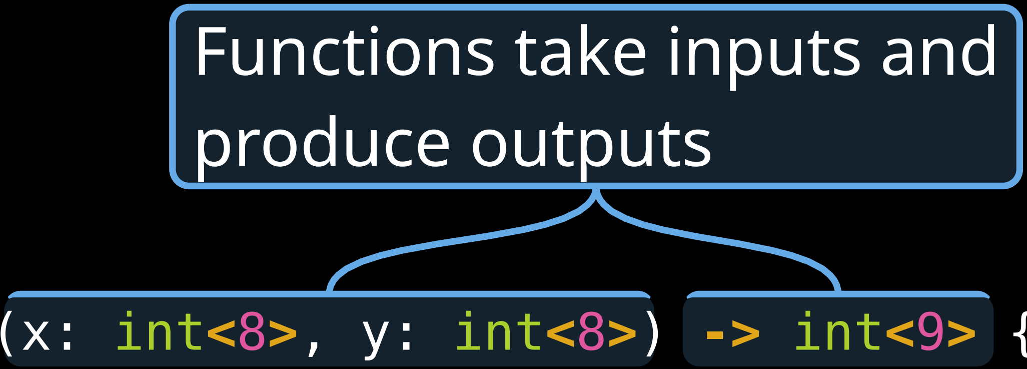
Spade



```
fn adder(x: int<8>, y: int<8>) -> int<9> {
  x + y
}
```



Functions take inputs and produce outputs

```
fn adder(x: int<8>, y: int<8>) -> int<9> {
  x + y
}
```

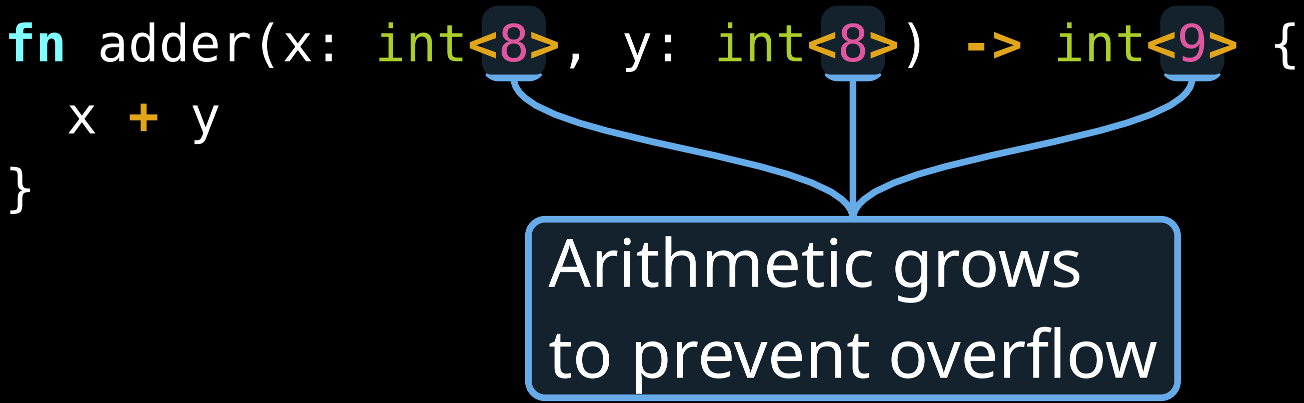
```
fn adder(x: int<8>, y: int<8>) -> int<9> {
  x + y
}
```

Standard math operators

+, -, *, &&, etc.

```
fn adder(x: int<8>, y: int<8>) -> int<9> {
  x + y
}
```

Last value in a block is returned



```
fn adder(x: int<8>, y: int<8>) -> int<9> {
  x + y
}
```

Arithmetic grows
to prevent overflow

```
fn adder(x: int<8>, y: int<8>) -> int<8>) {
  trunc(x + y)
}
```

```
fn adder(x: int<8>, y: int<8>) -> int<8>) {
  trunc(x + y)
}
```

`trunc` truncates back down

```
fn multiply_add(x: int<8>, y: int<8>, z: int<16>) -> int<17> {
  let sum = x * y
  sum + z
}
```

```
fn multiply_add(x: int<8>, y: int<8>, z: int<16>) -> int<17> {
  let sum = x * y
  sum + z
}
```

`let` defines new variables
(like `val` in Scala)

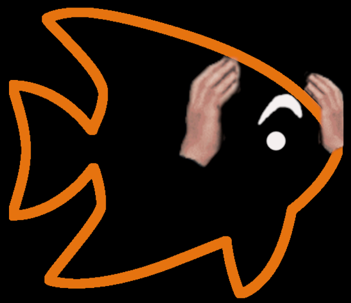
```
fn multiply_add(x: int<8>, y: int<8>, z: int<16>) -> int<17> {
  let sum = x * y
  sum + z
}
```

Typeinference infers types from context

`int<16>` in this case

```
fn multiply_add(x: int<8>, y: int<8>, z: int<16>) -> int<17> {
  let sum = x * y
  sum = sum + 1
  sum + z
}
```

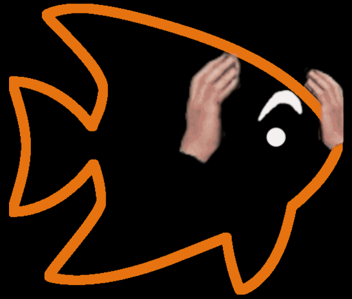
❗ Variables are immutable:
They can only be assigned once



```
fn select(select_a: bool, a: int<8>, b: int<8>) -> int<8> {
    let result = b;
    if select_a {
        result = a;
    }
    result
}
```

```
fn select(select_a: bool, a: int<8>, b: int<8>) -> int<8> {
    let result = b;
    if select_a {
        result = a;
    }
    result
}
```

❗ Mutation



```
fn select(select_a: bool, a: int<8>, b: int<8>) -> int<8> {

    let result = if select_a {
        a
    } else {
        b
    };

    result
}
```

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fn select(select_a: bool, a: int<8>, b: int<8>) -> int<8> {

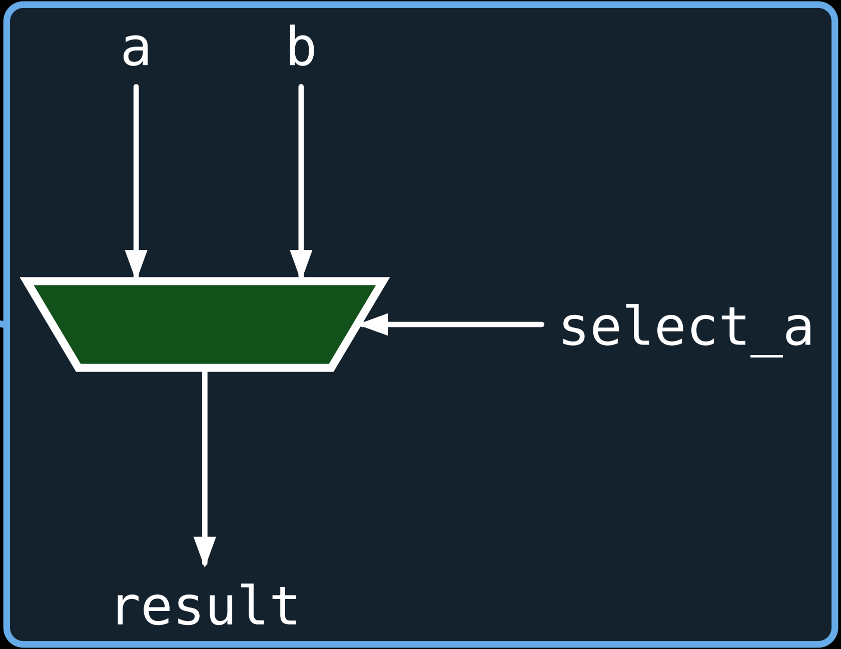
    let result = if select_a {
        a
    } else {
        b
    };

    result
}
```

If **expressions** *return* values

```
fn select(select_a: bool, a: int<8>, b: int<8>) -> int<8> {
    let result = if select_a {
        a
    } else {
        b
    };

    result
}
```



Sequential Logic

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on = !on;
  on
}
```

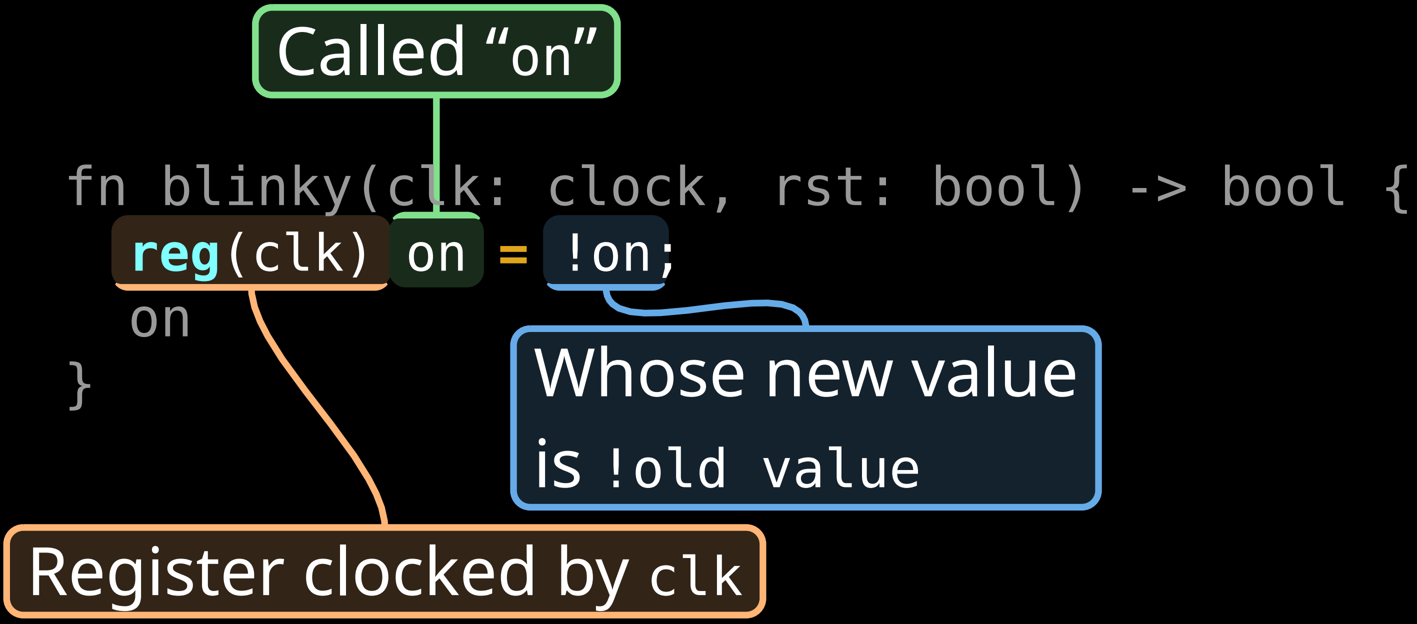
```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on = !on;
  on
}
```

Register clocked by `clk`

Called “on”

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on = !on;
  on
}
```

Register clocked by `clk`



Called “on”

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on = !on;
  on
}
```

Whose new value is `!old value`

Register clocked by `clk`

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on reset(rst: false) = !on;
  on
}
```

Reset to false when rst is true

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on reset(rst: false) = !on;
  on
}
```

```
error: register declared in function
   ┌─ src/main.spade:2:3
1  │ fn blinky(clk: clock, rst: bool) {
   │ -- this is a function
2  │   reg(clk) on = !on;
   │   ^^^ register not allowed here
   │
   = note: functions can only contain combinatorial logic
   = consider making the function an entity
1  │ entity blinky(clk: clock, rst: bool) {
   │ ~~~~~~
```

```
fn blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on reset(rst: false) = !on;
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```

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   │ ~~~~~~
```

```
entity blinky(clk: clock, rst: bool) -> bool {
  reg(clk) on reset(rst: false) = !on;
  on
}
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_000 / 2
}
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0

            counter + 1
        };

    counter > 10_000 / 2
}
```

Register called counter

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0

            counter + 1
        };

    counter > 10_000 / 2
}
```

Register called counter

Reset to 0

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_000 / 2
}
```

Next value = 0 if at max, otherwise reset to 0

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_000 / 2
}
```

Output is `true` if the counter is in its upper half

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_000 / 2
}
```

```
error: Type of expression is not fully known
  ┌─ src/main.spade:7:8
  │
7 │     if count == duration {
  │        ^^^^^ The type of this expression is not fully known
  │
  = note: Found incomplete type: Number<_>
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter: uint<15> reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_000 / 2
}
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            counter + 1
        };

    counter > 10_0
}
```

```
error: Expected type uint<15>, got Number<16>
  6 |     reg(clk) count: uint<15> reset(rst: 0) =
    |                           -- Type 15 inferred here
  7 | ╭       if count == duration {
  8 | │         0
  9 | │       } else {
 10 | │         count + 1
    | │         --------- Type 16 inferred here
 11 | │       };
    | ╰───────^ Expected uint<15>
    = note: Expected: 15 in: uint<15>
                 Got: 16 in: Number<16>
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            trunc(counter + 1)
        };

    counter > 10_000 / 2
}
```

```
entity blinky(clk: clock, rst: bool) -> bool {
    reg(clk) counter reset(rst: 0) =
        if counter == 10_000 {
            0
        } else {
            trunc(counter + 1)
        };

    counter > 10_000 / 2
}
```

Let’s try it on

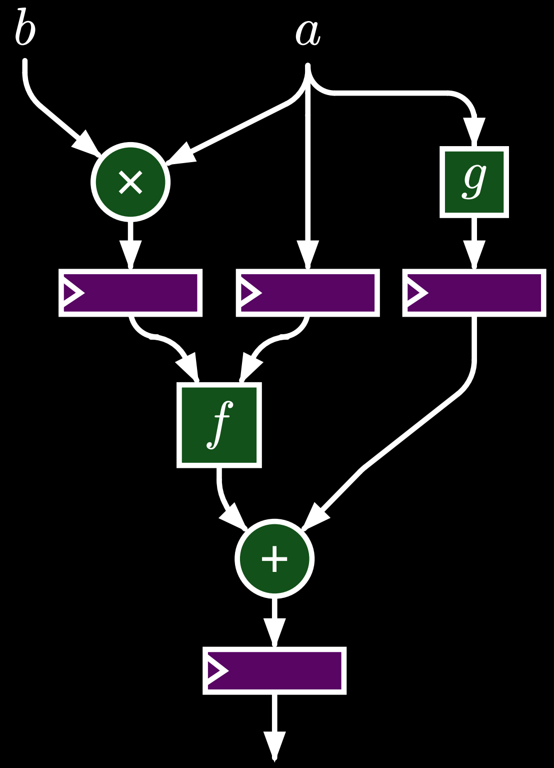
https://play.spade-lang.org

Pipelines and Timing

Pipelines

```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = g(a);
    let product = a*b;
reg;

    let sum = x + f(a, product);
reg;
    sum
}
```



Pipelines

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pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
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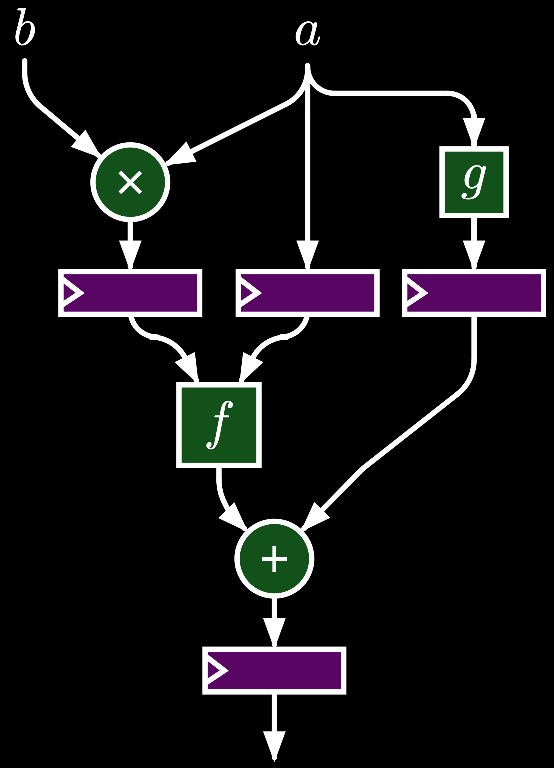
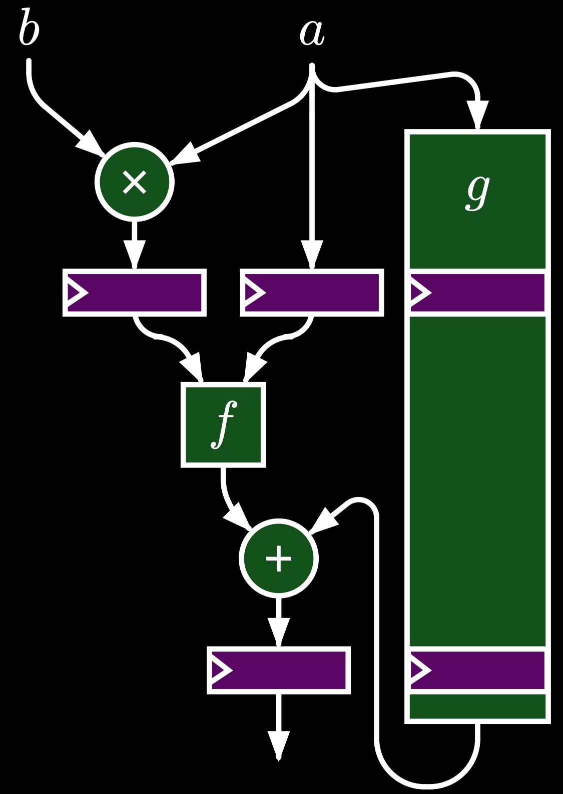


Pipelines

```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = g(a);
    let product = a*b;
reg;

    let sum = x + f(a, product);
reg;
    sum
}
```



Pipelines

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pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
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reg;

    let sum = x + f(a, product);
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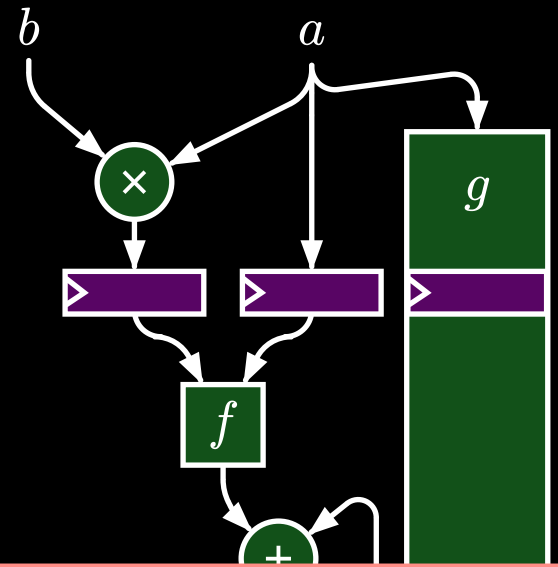
    sum
}
```

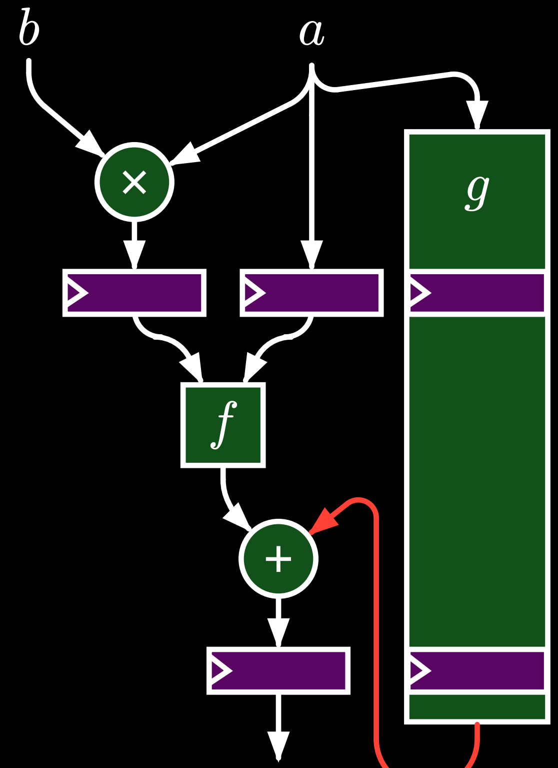


```
error: Expected `inst` and pipeline depth for pipeline instantiation
   ┌─ src/main.spade:3:13
   │
 3 │     let x = g(a);
   │             ^
   │             Expected pipeline instantiation
   │             Because g is a pipeline
   ·
   = Consider instantiating the pipeline with a depth
 3 │     let x = inst(/*depth*/) g(a);
                     +++++++++++
```

Pipelines

```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = inst(2) g(clk, a);
    let product = a*b;
reg;

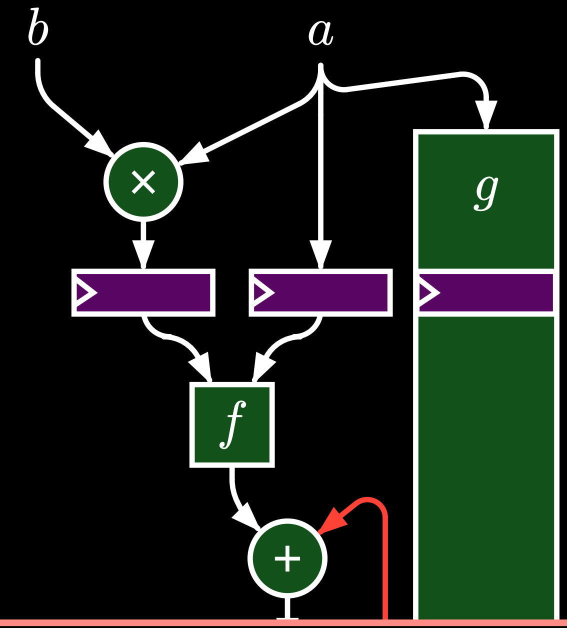
    let sum = x + f(a, product);
reg;
    sum
}
```



Pipelines

```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = inst(2) g(clk, a);
    let product = a*b;
reg;

    let sum = x + f(a, product);
reg;
    sum
}
```

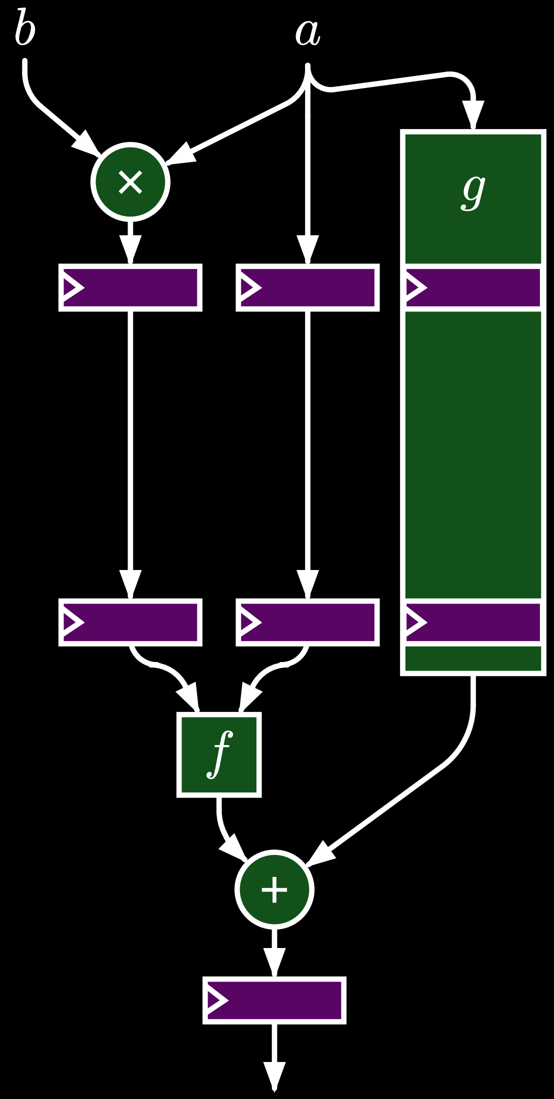


```
error: Use of x before it is ready
  ┌─ src/main.spade:7:15
3 │     let x = inst(2) g(a);
  │         - x is defined here at stage 0 with a latency of 2
  ·
7 │     let sum = x + f(a, product);
  │               ^
  │               x is unavailable for another 1 stage
  = help: Consider adding more reg; statements between
          the definition and use of x
```

Pipelines

```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = inst(2) g(clk, a);
    let product = a*b;
reg;

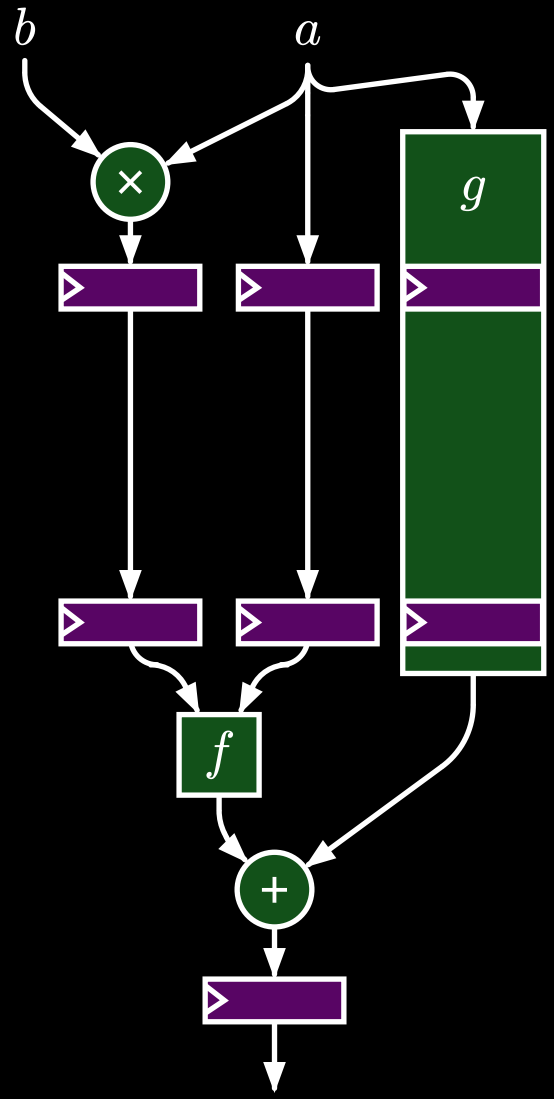
    let sum = x + f(a, product);
reg;
    sum
}
```



Pipelines

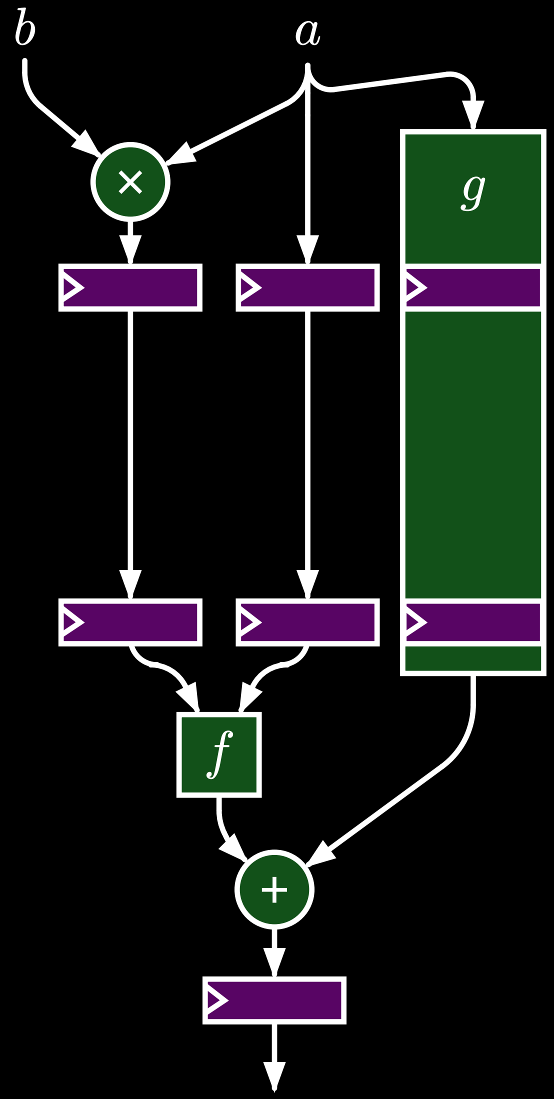
```
pipeline(2) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = inst(2) g(clk, a);
    let product = a*b;
reg;

    let sum = x + f(a, product);
reg;
    sum
}
```



Pipelines

```
pipeline(3) X(clk: clock, a: int<32>, b: int<32>)
    -> int<33> {
    let x = inst(2) g(clk, a);
    let product = a*b;
reg;
reg;
    let sum = x + f(a, product);
reg;
    sum
}
```



Instantiating Things

Definition:	**Instantiation**:
`fn trunc(...)`	`trunc(x + y)`
`entity blinky(...)`	`inst blinky(clk, rst)`
`pipeline(2) pipe(...)`	`inst(2) pipe(...)`

Definition:	**Instantiation:**
`fn trunc(...)`	`trunc(x + y)`
`entity blinky(...)`	`inst blinky(clk, rst)`
`pipeline(2) pipe(...)`	`inst(2) pipe(...)`

`fn` without keyword

Definition:

```
fn trunc(...)

entity blinky(...)

pipeline(2) pipe(...)
```

Instantiation:

```
trunc(x + y)

inst blinky(clk, rst)

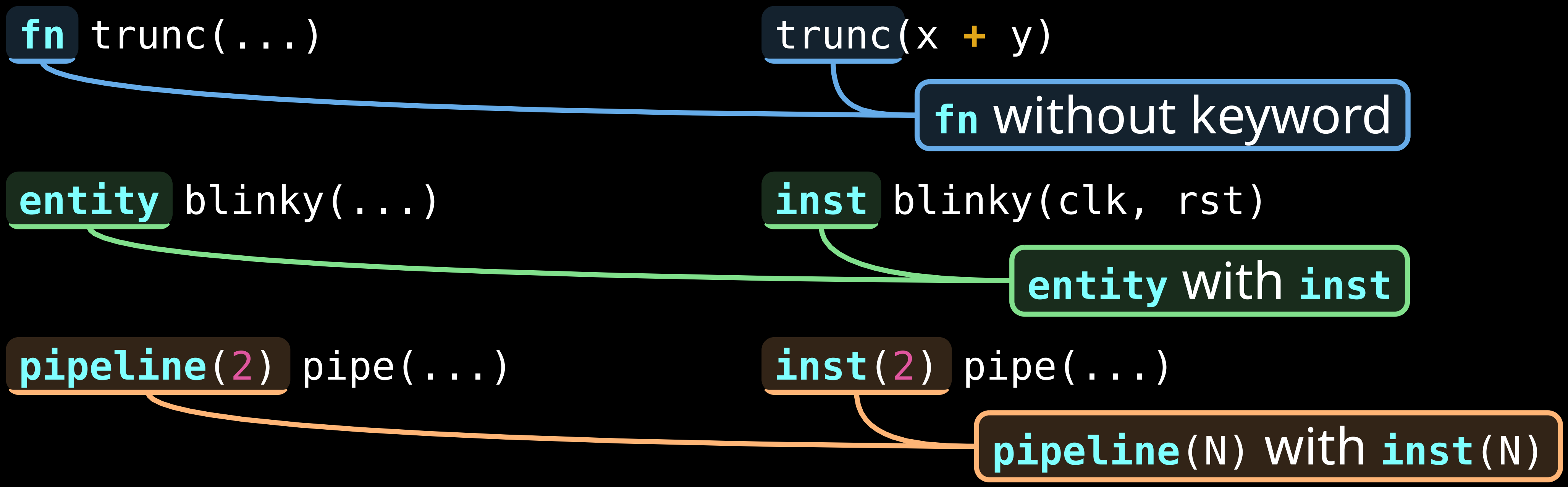
inst(2) pipe(...)
```

fn without keyword

entity with inst

Definition:

Instantiation:



```
fn trunc(...)
```

```
trunc(x + y)
```

fn without keyword

```
entity blinky(...)
```

```
inst blinky(clk, rst)
```

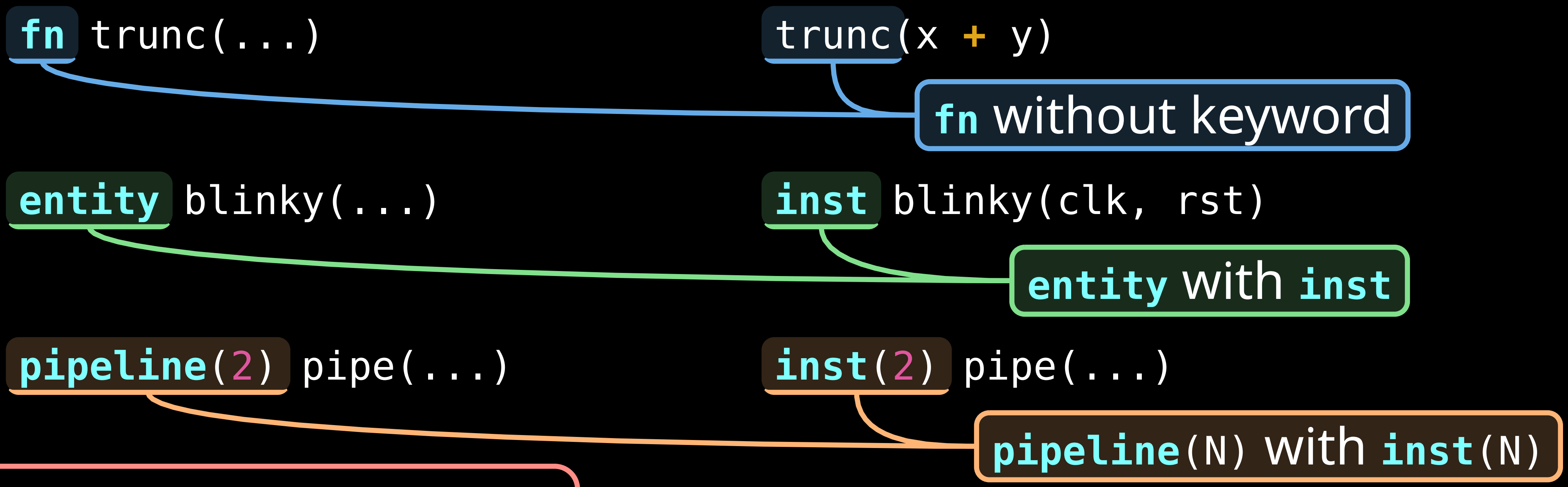
entity with inst

```
pipeline(2) pipe(...)
```

```
inst(2) pipe(...)
```

pipeline(N) with inst(N)

Definition: **Instantiation:**



`fn trunc(...)`

`trunc(x + y)`

`fn` without keyword

`entity blinky(...)`

`inst blinky(clk, rst)`

`entity` with `inst`

`pipeline(2) pipe(...)`

`inst(2) pipe(...)`

`pipeline(N)` with `inst(N)`

Encode assumptions!

Passing arguments

```
fn create_point(x: int<8>, y: int<8>)
```

Passing arguments

```
fn create_point(x: int<8>, y: int<8>)

// Positional arguments
create_point(5, 7)
```

Passing arguments

```
fn create_point(x: int<8>, y: int<8>)

// Positional arguments
create_point(5, 7)

// Named arguments
create_point$(y: 7, x: 5)
```

Passing arguments

```
fn create_point(x: int<8>, y: int<8>)

// Positional arguments
create_point(5, 7)

// Named arguments
create_point$(y: 7, x: 5)

// Shorthand named arguments
let x = ...
create_point$(x, y: 7)
```

Passing arguments

```
fn create_point(x: int<8>, y: int<8>)

// Positional arguments
create_point(5, 7)

// Named arguments
create_point$(y: 7, x: 5)

// Shorthand named arguments
let x = ...
create_point$(x, y: 7)
```

Same name in function as local

Types

```
// Primitive types
int<N>
uint<N>
bool
clock
```

Definition

```
struct Struct {
  x: int<8>,
  y: bool,
}
```

Definition

```
struct Struct {
  x: int<8>,
  y: bool,
}
```

Access

```
value.x
```

Definition

```
struct Struct {
  x: int<8>,
  y: bool,
}
```

Access

```
value.x
```

Instantiation

```
// Positional
Struct(x, y)
// Named
Struct$(x, y)
```

Tuples

Definition

```
(int<8>, bool)
```

Tuples

Definition

```
(int<8>, bool)
```

Access

```
value#0
```

Tuples

Definition

```
(int<8>, bool)
```

Access

```
value#0
```

Instantiation

```
(5, true)
```

Arrays

Definition

```
[int<8>; 3]
```

Arrays

Definition

```
[int<8>; 3]
```

Access

```
value[i]

value[0..1]
```

Arrays

Definition

```
[int<8>; 3]
```

Access

```
value[i]

value[0..1]
```

Instantiation

```
[1, 2, 3]
```

Destructuring

```
let (x, y) = value;
```

Destructuring

```
let (x, y) = value;

let [x, y] = array;
```

Destructuring

```
let (x, y) = value;

let [x, y] = array;

let Struct(x, y) = value;
```

Destructuring

```
let (x, y) = value;

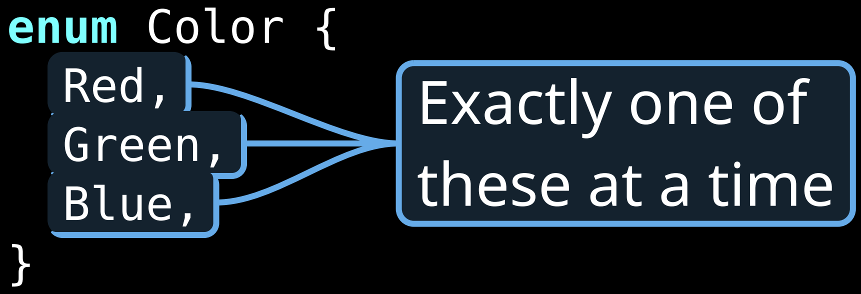
let [x, y] = array;

let Struct$(x, y) = value;
```

Can also be named arguments

More Interesting Types

```
enum Color {
  Red,
  Green,
  Blue,
}
```



```
enum Color {
  Red,
  Green,
  Blue,
}
```

Exactly one of these at a time

```
enum Color {
  Red,
  Green,
  Blue,
}
```

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
  }
}
```

```
enum Color {
  Red,
  Green,
  Blue,
  Grayscale {
    brightness: uint<8>
  },
  Custom {
    r: uint<8>,
    g: uint<8>,
    b: uint<8>
  },
}
```

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
  }
}
```

```
enum Color {
  Red,
  Green,
  Blue,
  Grayscale {
    brightness: uint<8>
  },
  Custom {
    r: uint<8>,
    g: uint<8>,
    b: uint<8>
  },
}
```

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
    Color::Grayscale(b) => [b, b, b],
  }
}
```

```
enum Color {
  Red,
  Green,
  Blue,
  Grayscale {
    brightness: uint<8>
  },
  Custom {
    r: uint<8>,
    g: uint<8>,
    b: uint<8>
  },
}
```

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
    Color::Grayscale(b) => [b, b, b],
  }
}
```

Match accesses the payload

So it can be used in the result

```
enum Color {
  Red,
  Green,
  Blue,
  Grayscale {
    brightness: uint<8>
  },
  Custom {
    r: uint<8>,
    g: uint<8>,
    b: uint<8>
  },
}
```

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
    Color::Grayscale(b) => [b, b, b],
    Color::Custom$(r, g, b) => [r, g, b],
  }
}
```

Enum Example: `Option`

```
enum Option<T> {
  None,
  Some{val: T}
}
```

Enum Example: `Option`

Either `None`

```
enum Option<T> {
  None,
  Some{val: T}
}
```

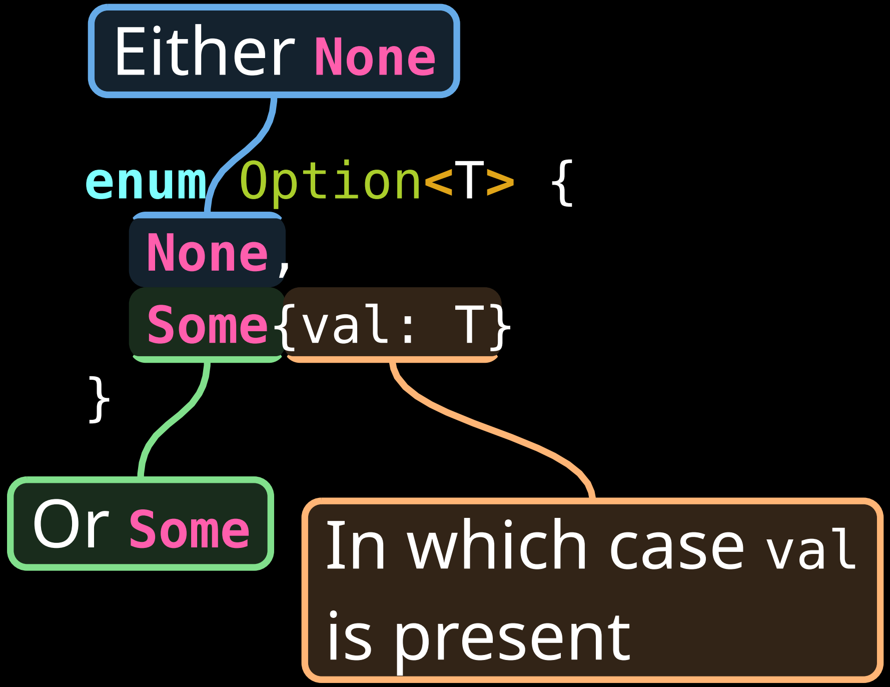
Enum Example: `Option`

Either `None`

```
enum Option<T> {
  None,
  Some{val: T}
}
```

Or `Some`

Enum Example: `Option`



Either `None`

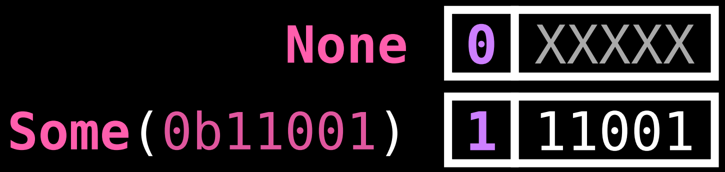
```
enum Option<T> {
  None,
  Some{val: T}
}
```

Or `Some`

In which case `val` is present

Enum Example: `Option`

```
enum Option<T> {
  None,
  Some{val: T}
}
```



```
         None  | 0 | XXXXX |
Some(0b11001)  | 1 | 11001 |
```

Enum Example: `Option`

```
enum Option<T> {
  None,
  Some{val: T}
}
```

None	0	XXXXX
Some(0b11001)	1	11001

Intuitively: valid signal + validated data

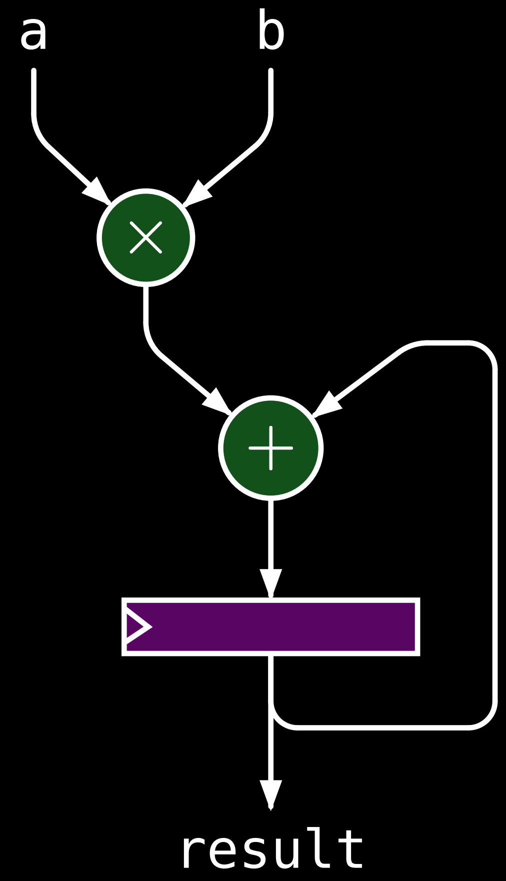
Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {






}
```

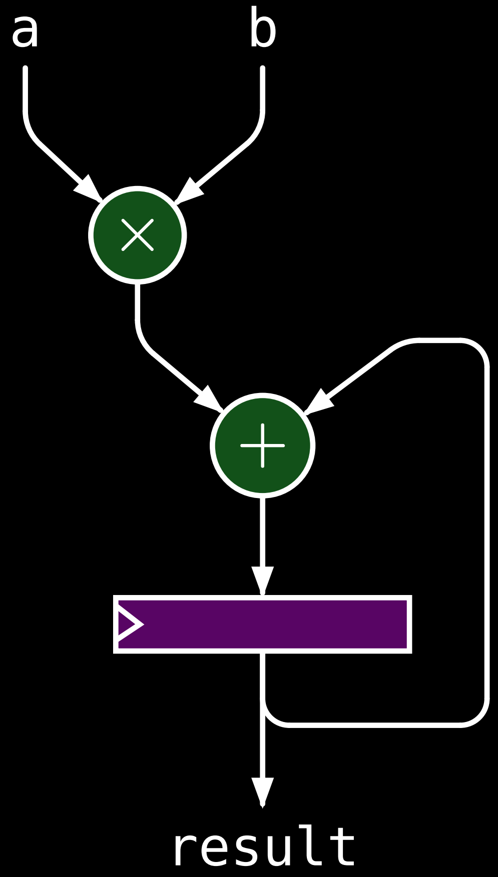


Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;




}
```

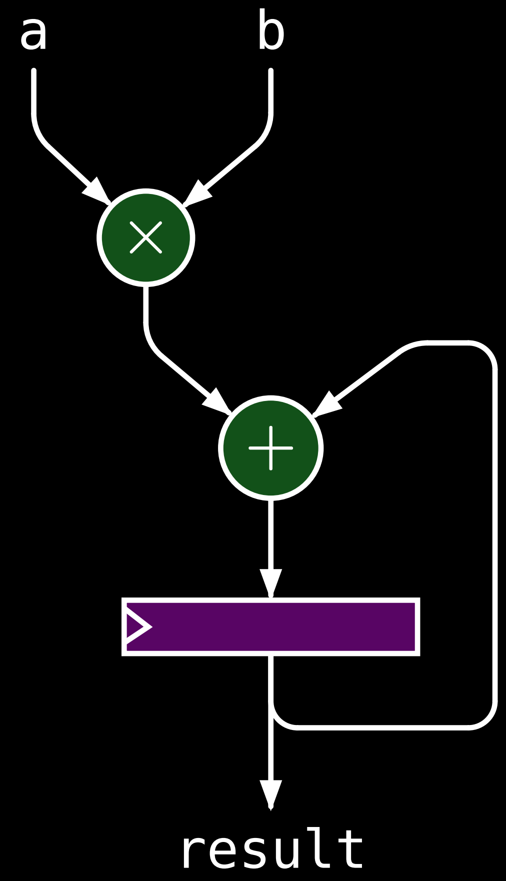


Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
          product + sum;


}
```

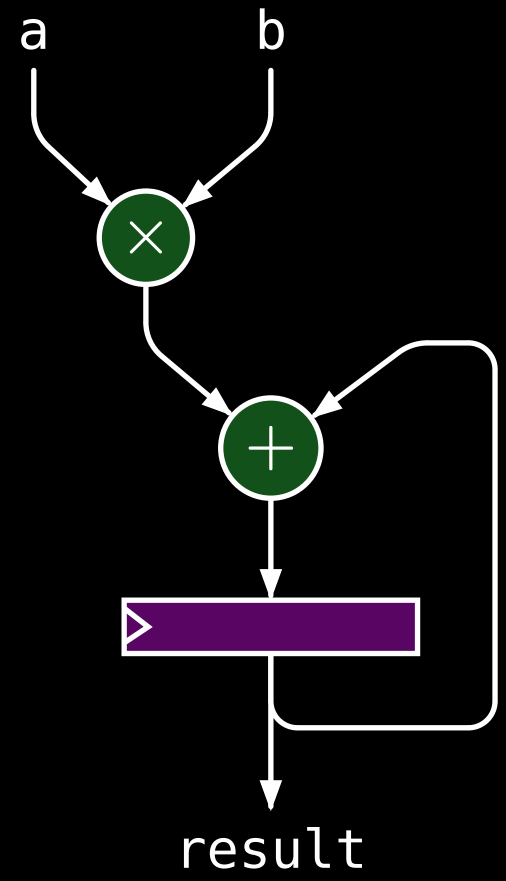


Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
          product + sum;


  sum
}
```

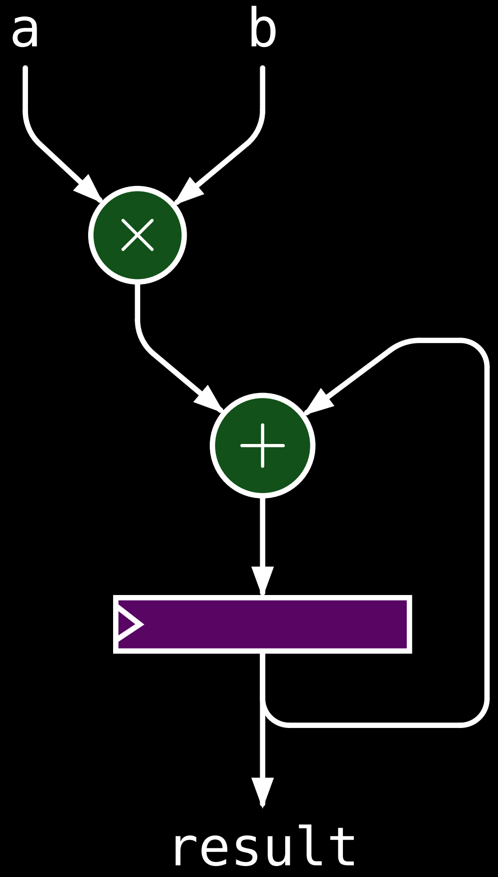


Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
          sext(product) + trunc(sum);

  sum
}
```

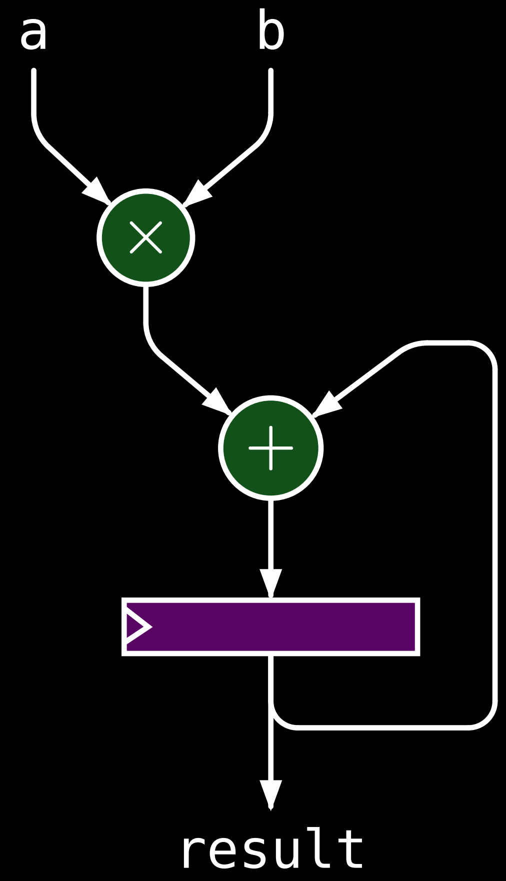


Option Example: MAC

```
entity mac(
  clk: clock, rst: bool,
  input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
          product + sum;


  sum
}
```



Option Example: MAC

```
entity data_producer(...)
    -> (int<16>, int<16>)
{...}


let mac_in = inst data_producer(...)

let mac_out = inst mac(clk, rst, mac_in);
```

Option Example: MAC

```
entity data_producer(...)
    -> (int<16>, int<16>)
{...}


let mac_in = inst data_producer(...)

let mac_out = inst mac(clk, rst, mac_in);
```

❗ **Requirement change**

Data is not produced every clock cycle

Option Example: MAC

```
entity data_producer(...)
    -> (int<16>, int<16>)
{...}


let mac_in = inst data_producer(...)

let mac_out = inst mac(clk, rst, mac_in);
```

Option Example: MAC

```
entity data_producer(...)
    -> Option<(int<16>, int<16>)>
{...}


let mac_in = inst data_producer(...)

let mac_out = inst mac(clk, rst, mac_in);
```

Option Example: MAC

```
entity data_producer(...)
    -> Option<(int<16>, int<16>)>
{...}


let mac_in = inst data_producer(...)

let mac_out = inst mac(clk, rst, mac_in);
```

Now `Option<...>`

❗ Type error

```
entity mac(
  clk: clock, rst: bool, input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: (int<16>, int<16>)
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let (a, b) = input;
  let product = a * b;

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

Not available every clock cycle anymore

❗ Type error

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => ...,
      None => ...,
  }]

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => ...,
  }]

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

Next compile error

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      sext(product) + trunc(sum);

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      match product {
        Some(product) => sum + product,
        None => sum
      }

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      match product {
        Some(product) => sum + product,
        None => sum
      }

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum reset(rst: 0) =
      match product {
        Some(product) => sum + product,
        None => sum
      }

  sum
}
```

```
entity mac(
  clk: clock, rst: bool, input: Option<(int<16>, int<16>)>
) -> int<40> {
  let product = match input {
      Some((a, b)) => Some(a * b),
      None => None,
  }]

  reg(clk) sum
      match product {
        Some(product) => sum + product,
        None => sum
      }

  sum
}
```

Once per sample,
or continuous output?

Enum example: FSMs

Make an LED blink thrice whenever a button is pressed

```
while True:
  if btn:
    for i in range(0, 3):
      led_on()
      wait(delay)
      led_off()
      wait(delay)
```

```
enum State {


}
```

```
while True:
  if btn:
    for i in range(0, 3):
      led_on()
      wait(delay)
      led_off()
      wait(delay)
```

```
enum State {
  Idle,

}
```

Wait for something to happen

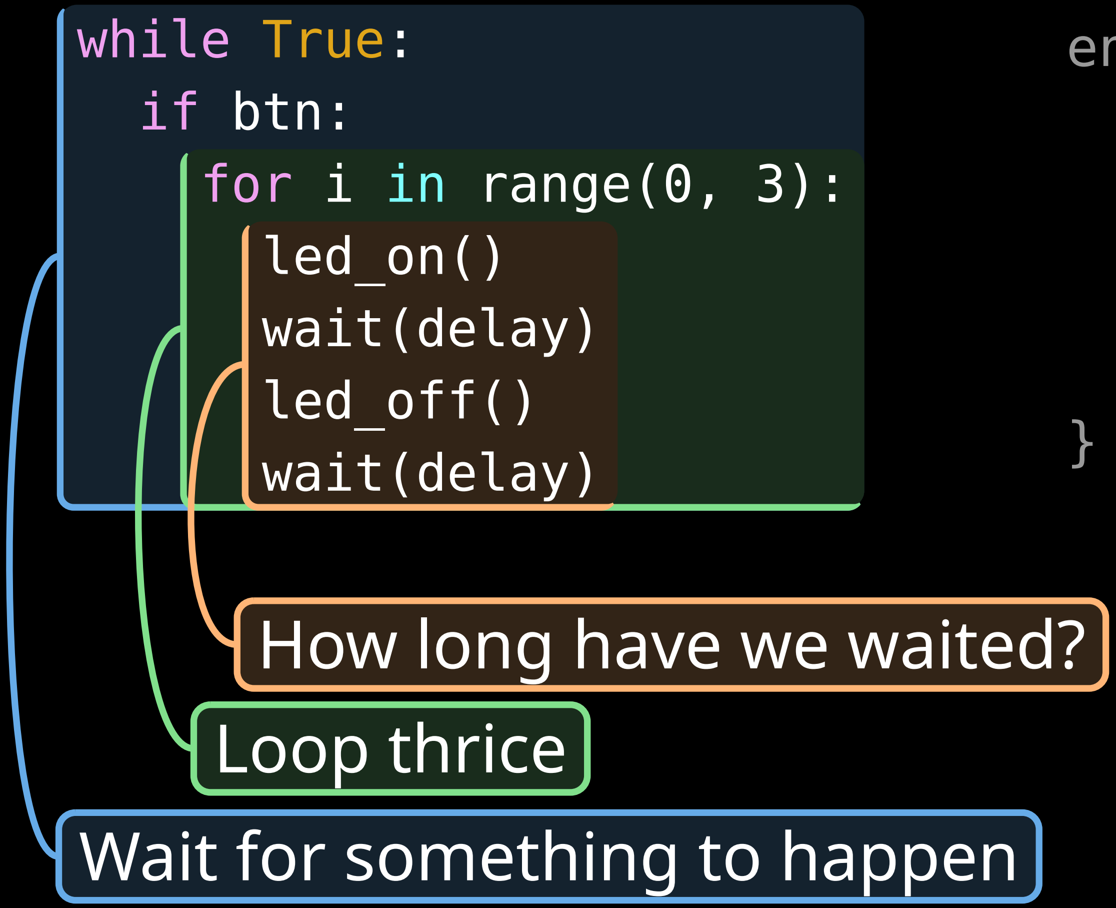
```
while True:
  if btn:
    for i in range(0, 3):
      led_on()
      wait(delay)
      led_off()
      wait(delay)
```

Loop thrice

Wait for something to happen

```
enum State {
  Idle,
  Blink {
    blinks_left: uint<3>,

  }
}
```



```
while True:
  if btn:
    for i in range(0, 3):
      led_on()
      wait(delay)
      led_off()
      wait(delay)
```

How long have we waited?

Loop thrice

Wait for something to happen

```
enum State {
  Idle,
  Blink {
    blinks_left: uint<3>,
    on_duration: uint<15>,
  }
}
```

```
while True:
  if btn:
    for i in range(0, 3):
      led_on()
      wait(delay)
      led_off()
      wait(delay)
```

```
enum State {
  Idle,
  Blink {
    blinks_left: uint<3>,
    on_duration: uint<15>,
  }
}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{




}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =



}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {




    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) =>


    }


}
```

Match works on tuples

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) =>



    }


}
```

And supports patterns

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,



    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),


    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),


    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left, duration), _) => ???,

    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => Stat
      (State::Idle, true) =>
        State::Blink$(blinks_left:

      (State::Blink$(blinks_left, duration), _) => ???,

    }


}
```

We don’t care about the input while blinking

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left, duration), _) => ???,

    }

}
```

Back to idle
or more blinks?

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left, duration), _) => ???,

    }


}
```

Are we done waiting?

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,

    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,
      (State::Blink$(blinks_left, duration: 0), _) =>
          State::Blink$(blinks_left: trunc(blinks_left-1), duration: 10_000),

    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,
      (State::Blink$(blinks_left, duration: 0), _) =>
          State::Blink$(blinks_left: trunc(blinks_left-1), duration: 10_000),

    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,
      (State::Blink$(blinks_left, duration: 0), _) =>
          State::Blink$(blinks_left: trunc(blinks_left-1), duration: 10_000),
      (State::Blink$(blinks_left, duration), _) =>
          State::Blink(blinks_left, trunc(duration_left - 1))
    }


}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,
      (State::Blink$(blinks_left, duration: 0), _) =>
          State::Blink$(blinks_left: trunc(blinks_left-1), duration: 10_000),
      (State::Blink$(blinks_left, duration), _) =>
          State::Blink(blinks_left, trunc(duration_left - 1))
    }


}
```

Prioritized in order

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
    match (state, input) {
      (State::Idle, false) => State::Idle,
      (State::Idle, true) =>
        State::Blink$(blinks_left: 2, duration: 10_000),

      (State::Blink$(blinks_left: 0, duration: 0), _) =>
          State::Idle,
      (State::Blink$(blinks_left, duration: 0), _) =>
          State::Blink$(blinks_left: trunc(blinks_left-1), duration: 10_000),
      (State::Blink$(blinks_left, duration), _) =>
          State::Blink(blinks_left, trunc(duration_left - 1))
    }


}
```

The compiler will check your work. Missing cases are errors

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
     ...

  match state {


  }
}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
     ...

  match state {
    State::Idle => false,

  }
}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
     ...

  match state {
    State::Idle => false,
    State::Blink$(blinks_left: _, duration_left) => ...,
  }
}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
     ...

  match state {
    State::Idle => false,
    State::Blink$(blinks_left: _, duration_left) =>
        duration_left < 10_000 / 2,
  }
}
```

```
entity blink_thrice(clk: clock, rst: bool, btn: bool)
    -> bool
{
  reg(clk) state reset(rst: State::Idle) =
     ...

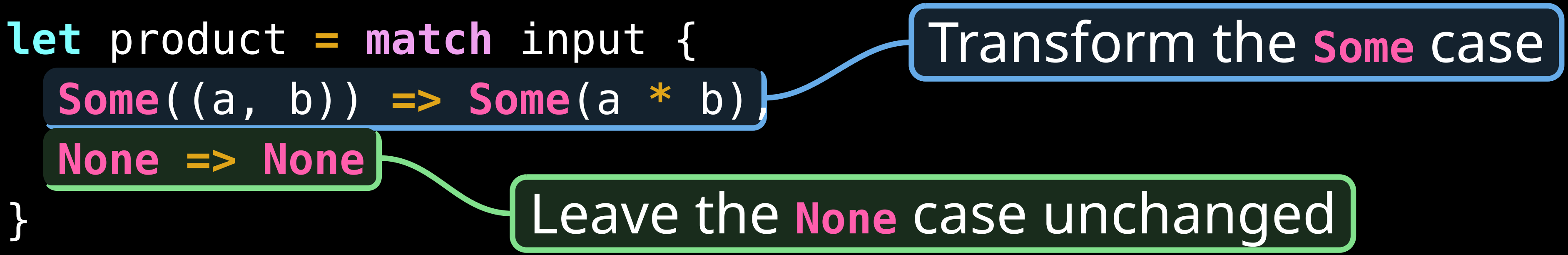
  match state {
    State::Idle => false,
    State::Blink$(blinks_left: _, duration_left) =>
        duration_left < 10_000 / 2,
  }
}
```

Methods

```rust
let product = match input {
  Some((a, b)) => Some(a * b),
  None => None
}
```

```
let product = match input {
  Some((a, b)) => Some(a * b),
  None => None
}
```

Transform the `Some` case



```
let product = match input {
    Some((a, b)) => Some(a * b),
    None => None
}
```

Transform the Some case

Leave the None case unchanged

```
product.map(...)
product.map(...)
```

Transform the contained value

```
product.map(fn ((a, b)) { a * b })
```

Transform the contained value

Using a lambda function

```
fn to_rgb(color: Color) -> [uint<8>; 3] {
  match color {
    Color::Red => [255, 0, 0],
    Color::Green => [0, 255, 0],
    Color::Blue => [0, 0, 255],
    Color::Grayscale(b) => [b, b, b],
    Color::Custom$(r, g, b) => [r, g, b],
  }
}
```

```
impl Color {
  fn to_rgb(self) -> [uint<8>; 3] {
    match self {
      Color::Red => [255, 0, 0],
      Color::Green => [0, 255, 0],
      Color::Blue => [0, 0, 255],
      Color::Grayscale(b) => [b, b, b],
      Color::Custom$(r, g, b) => [r, g, b],
    }
  }
}
```

```
struct port Rv<T> {
  data: &Option<T>,
  ready: inv &bool
}
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_ethernet_bytes(clk, rst);
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_ethernet_bytes(clk, rst);
```

```
error Option<_> has no method into_ethernet_bytes
 ┌─ src/main.spade:3
 │
2│ let pins = camera_feed
 │            ~~~~~~~~~~~ This has type Option<_>
3│   .inst into_ethernet_bytes()
 │         ^^^^^^^^^^^^^^^^^^^ No such method
 help: The method exists for Rv<_>
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst into_ethernet_bytes(clk, rst);
```

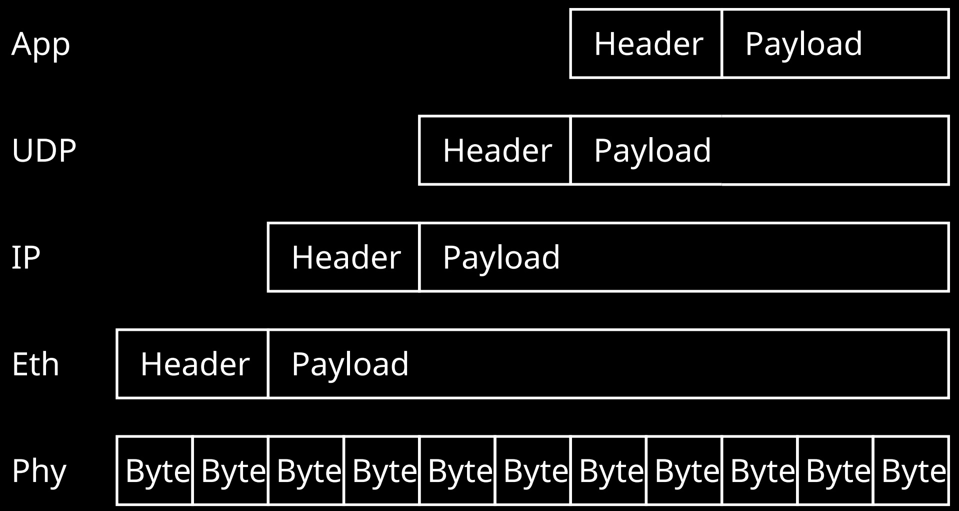
```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_ethernet_bytes(clk, rst);
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_ethernet_bytes(clk, rst);
```

```
error Rv<PixelsPackets> has no method
      into_ethernet_bytes
   ┌─ src/main.spade:5
   │
2  │   let eth_pins = udp_stream
   │  ┌─────────────────────────────────────────'
3  │  │     .inst into_rv_fifo::<1024>()
4  │  │     .inst packetize$(len: 1480)
   │  └─────' This has type Rv<PixelPackets>
5  │        .inst into_ethernet_bytes(clk, rst)
   │              ^^^^^^^^^^^^^^^^^^^ No such method
 help: The method exists for Rv<IpPackets>
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)

.inst into_ethernet_bytes(clk, rst);
```



App: Header | Payload

UDP: Header | Payload

IP: Header | Payload

Eth: Header | Payload

Phy: Byte | Byte | Byte | Byte | Byte | Byte | Byte | Byte | Byte | Byte | Byte

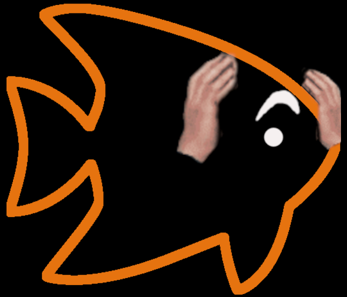
```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ethernet_bytes(clk, rst);
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

Oh no, we forgor💀 about timing.



```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst buffer_headers()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
  .inst buffer()
```

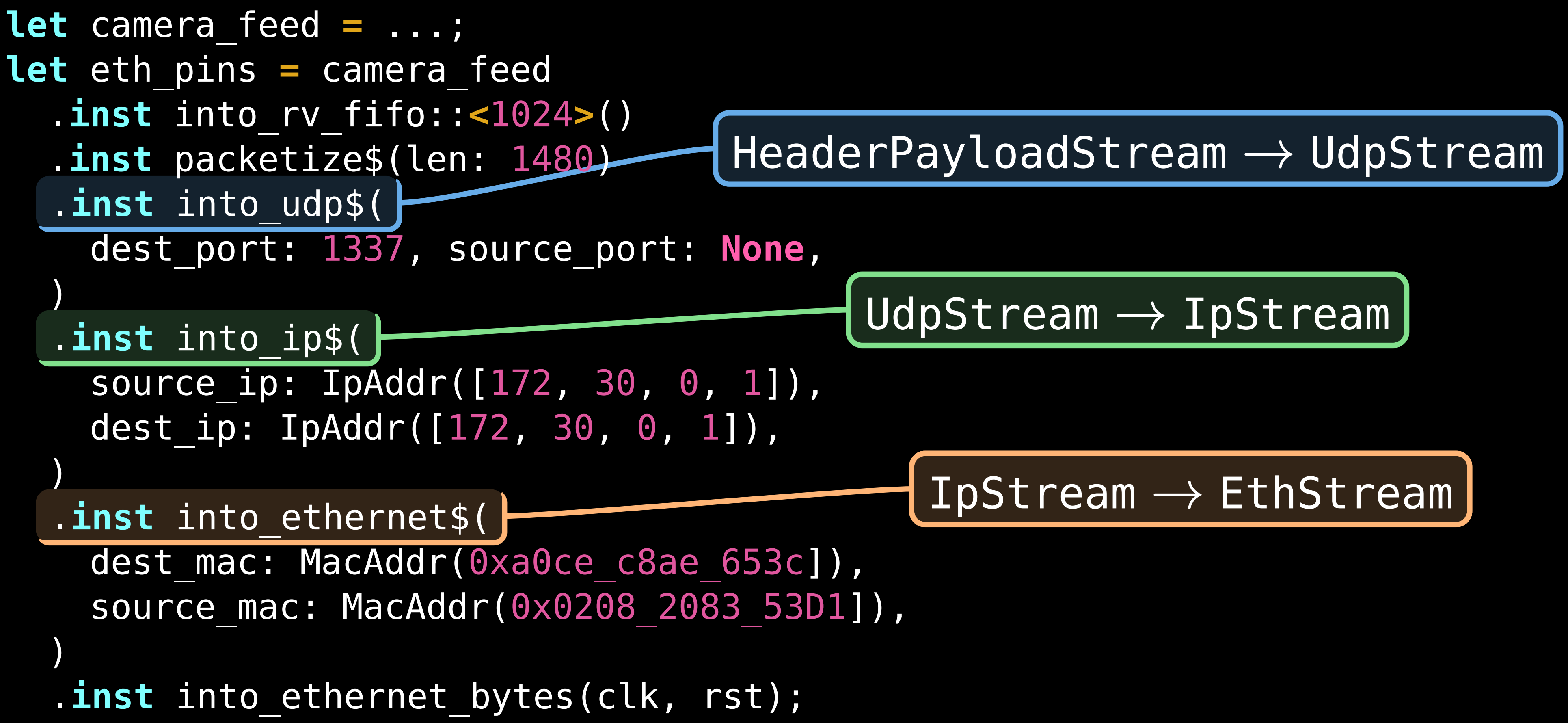
```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst buffer_headers()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
  .inst buffer()
```

HeaderPayloadStream → UdpStream

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst buffer_headers()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

HeaderPayloadStream ⟶ UdpStream

UdpStream ⟶ IpStream



```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

HeaderPayloadStream → UdpStream

UdpStream → IpStream

IpStream → EthStream

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst into_ethernet_bytes(clk, rst);
```

HeaderPayloadStream → UdpStream

UdpStream → IpStream

IpStream → EthStream

Type safe transformations

```
let camera_feed = ...;
let eth_pins = camera_feed
  .inst into_rv_fifo::<1024>()
  .inst packetize$(len: 1480)
  .inst into_udp$(
    dest_port: 1337, source_port: None,
  )
  .inst into_ip$(
    source_ip: IpAddr([172, 30, 0, 1]),
    dest_ip: IpAddr([172, 30, 0, 1]),
  )
  .inst into_ethernet$(
    dest_mac: MacAddr(0xa0ce_c8ae_653c]),
    source_mac: MacAddr(0x0208_2083_53D1]),
  )
  .inst append_lower_priority(inst handle_arp_icmp(...))
  .inst into_ethernet_bytes(clk, rst);
```

Respond to pings and
Address Resolution Requests

Tooling

Tooling

Will make or break a language

Compiler

- Takes your Spade, emits Verilog
- More importantly, provides helpful and guiding **error messages**

The Swim build tool

- Manages dependencies
- Runs synthesis tools
- Installs CAD tools

Editor Integration with LSP

Provide that 0.1 second interactivity where possible

Tests

Tests

- Spade is designed for *synthesizeable* hardware

Tests

- Spade is designed for *synthesizeable* hardware
- Testbenches are largely a software problem

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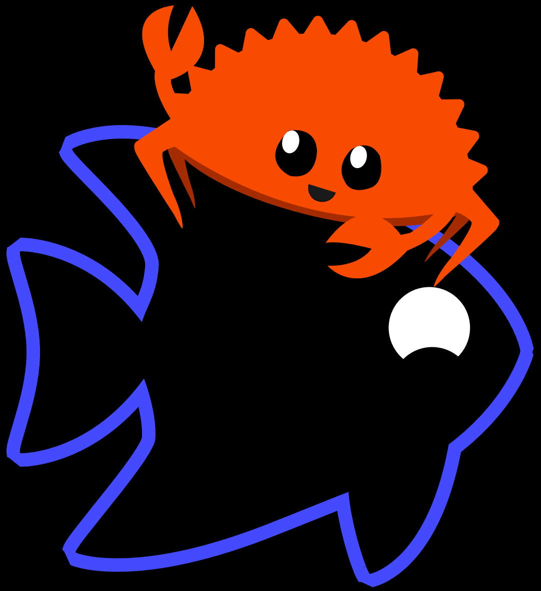

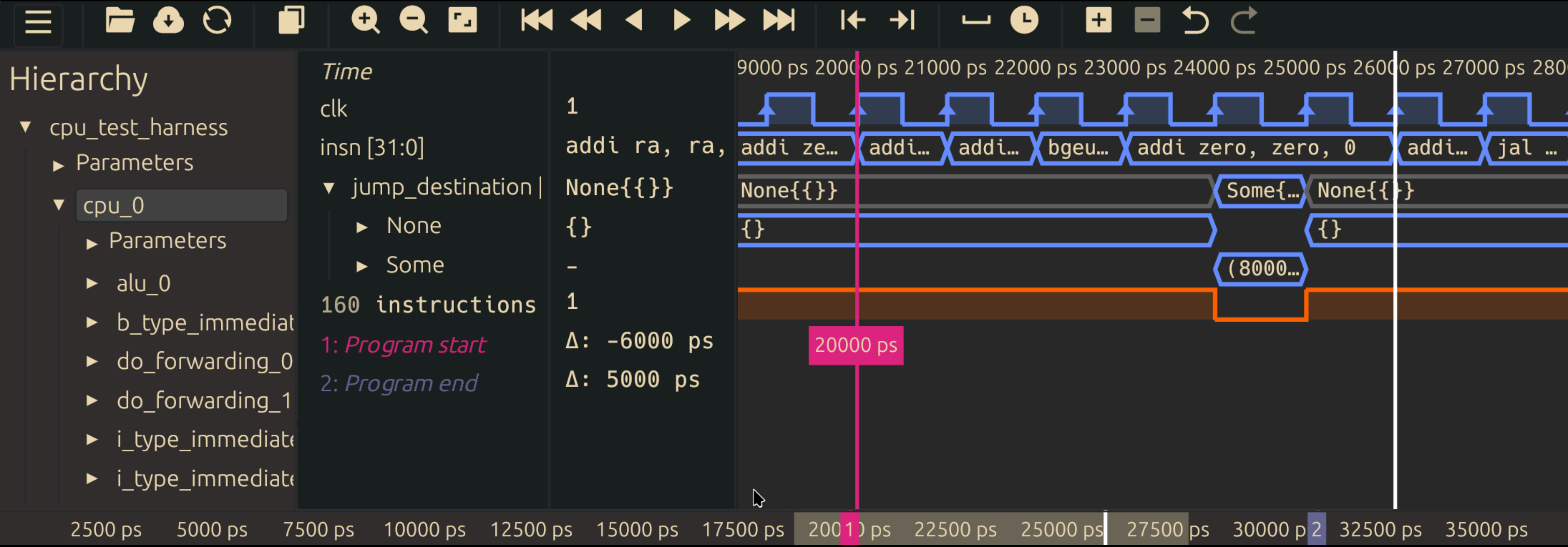

Hierarchy

- ▼ cpu_test_harness
  - ▸ Parameters
  - ▼ cpu_0
    - ▸ Parameters
    - ▸ alu_0
    - ▸ b_type_immediat
    - ▸ do_forwarding_0
    - ▸ do_forwarding_1
    - ▸ i_type_immediate
    - ▸ i_type_immediate

Time	
clk	1
insn [31:0]	addi ra, ra,
▼ jump_destination		None{{}}
▸ None	{}
▸ Some	-
160 instructions	1
1: *Program start*	Δ: -6000 ps
2: *Program end*	Δ: 5000 ps

Surrounding tooling

- Documentation generation
- Auto-formatting
- More powerful LSP

Conclusions

Use your language to

- *encode* your assumptions
- *alert you* when you violate them
- *guide* you when refactoring

Lab time!

Play with Spade’s unique features

- Pipelining
- Type system

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https://docs.spade-lang.org, go to the **Agile Hardware Design Tutorial**

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Estimating difficulty is hard, do task 1 and 2 in both parts first