CS448h: Lua and Terra

Zach DeVito

Last Time

Do an Image Blur

```
local r =   (a + a:shift(-1,0)
               + a:shift(0,1)
               + a:shift(0,-1)
               + a:shift(1,0)) / 5.0
```

Our Lua implementation: 0.27 MP/s

Naive C loop doing the same thing: 48.2 MP/s

Why?

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Naive C loop doing the same thing: 48.2 MP/s

Why?

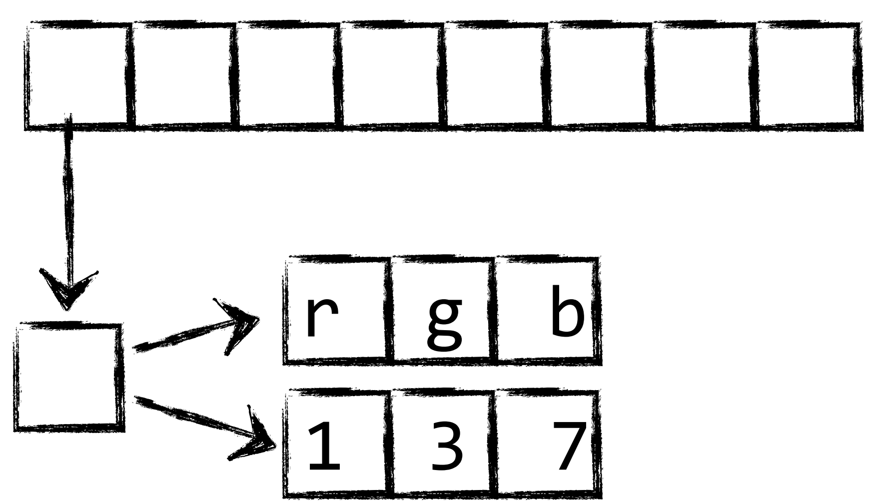
- Our storage of the image is inefficient Lua data structures and operations
- We are doing individual operations on the entire image, the C code just does it in one pass

Inefficient Data Structures and Operators

```
for i = 0, self.width * a - 1 do
    local l,r = self.data[i],rhs.data[i]
    result.data[i] = { r = l.r + r.r, g = l.g + r.g, b = l.b + r.b }
end
```

All hash-table lookups.

Data-layout:



Order of Image operations

```
local r =   (a - a:shift(-1,0)
               - a:shift(0,1)
               - a:shift(0,-1)
               - a:shift(1,0)) / 5.0
```

```
For each pixel:
  shift by -1,0
For each pixel:
  subtract
For each pixel:
  shift by 0,1
For each pixel:
  subtract
For each pixel:
  shift by 0,-1
For each pixel:
  subtract
For each pixel:
  shift by 1,0
For each pixel:
  subtract
```

```
For each pixel:
  set to 5.0
For each pixel:
  divide
```

High level specification is nice but the order of the operations is a really bad idea.

Order of Image operations

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```
For each pixel:
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```

High level specification is nice but the order of the operations is a really bad idea.

How bad is it?

Estimating Performance

Physical limits of your computer:

- Bandwidth to main memory (~20--30GB/s)
- FLOPs (~30--60 GFLOPS double precision per core)

Each shift:
  2 passes (read,write) x 4
Each math op:
  3 passes (read,read,write) x 5
Each constant:
  1 pass (write) x 1

24 passes

Single Loop: 2 passes (read, write)

Some of these inefficiencies are fixable in Lua itself:

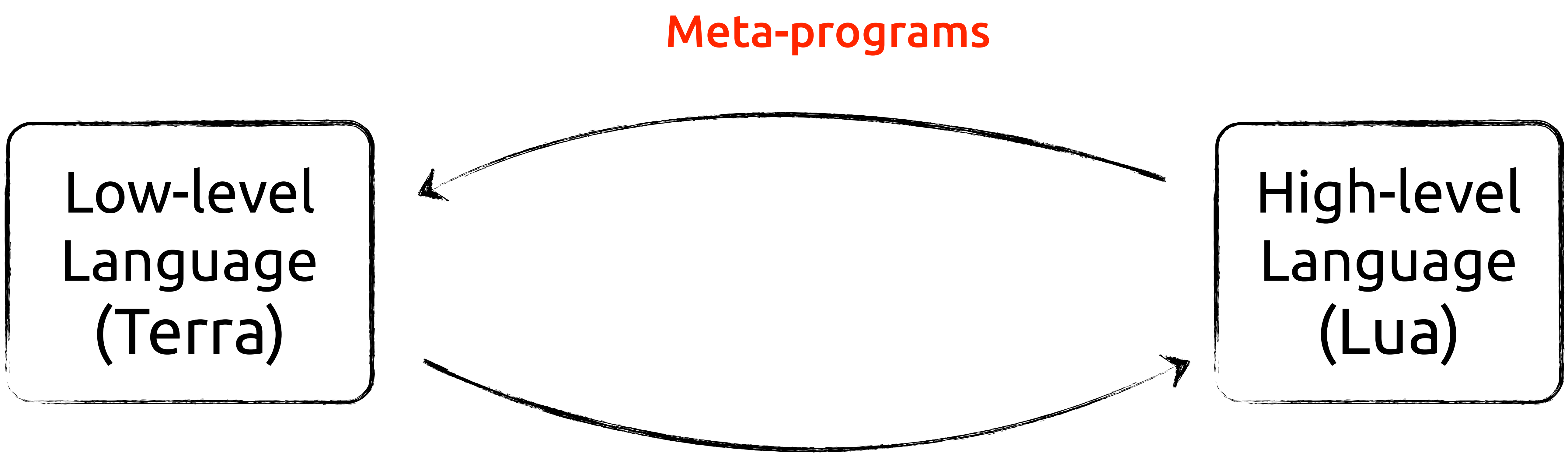
- Use a flat RGB array for data.

Others would be difficult to fix:

- Get code into a single loop, but still keep the high-level representation.
- Use only three bytes for each pixel

Specify the operation in a **high-level language**,
then transform it into code in a **low-level language**.

Our approach: A Two-language design



Combining High- and Low-level Languages

Web Server Development

Database Language (C/C++),

ORM layer, Business Logic (Ruby)

Scientific Computing

MATLAB, C++/FORTRAN

Game Programming

Shading Language (OpenGL), Scripting Language (Lua),

Engine Language (C++)

Integrating existing languages is problematic

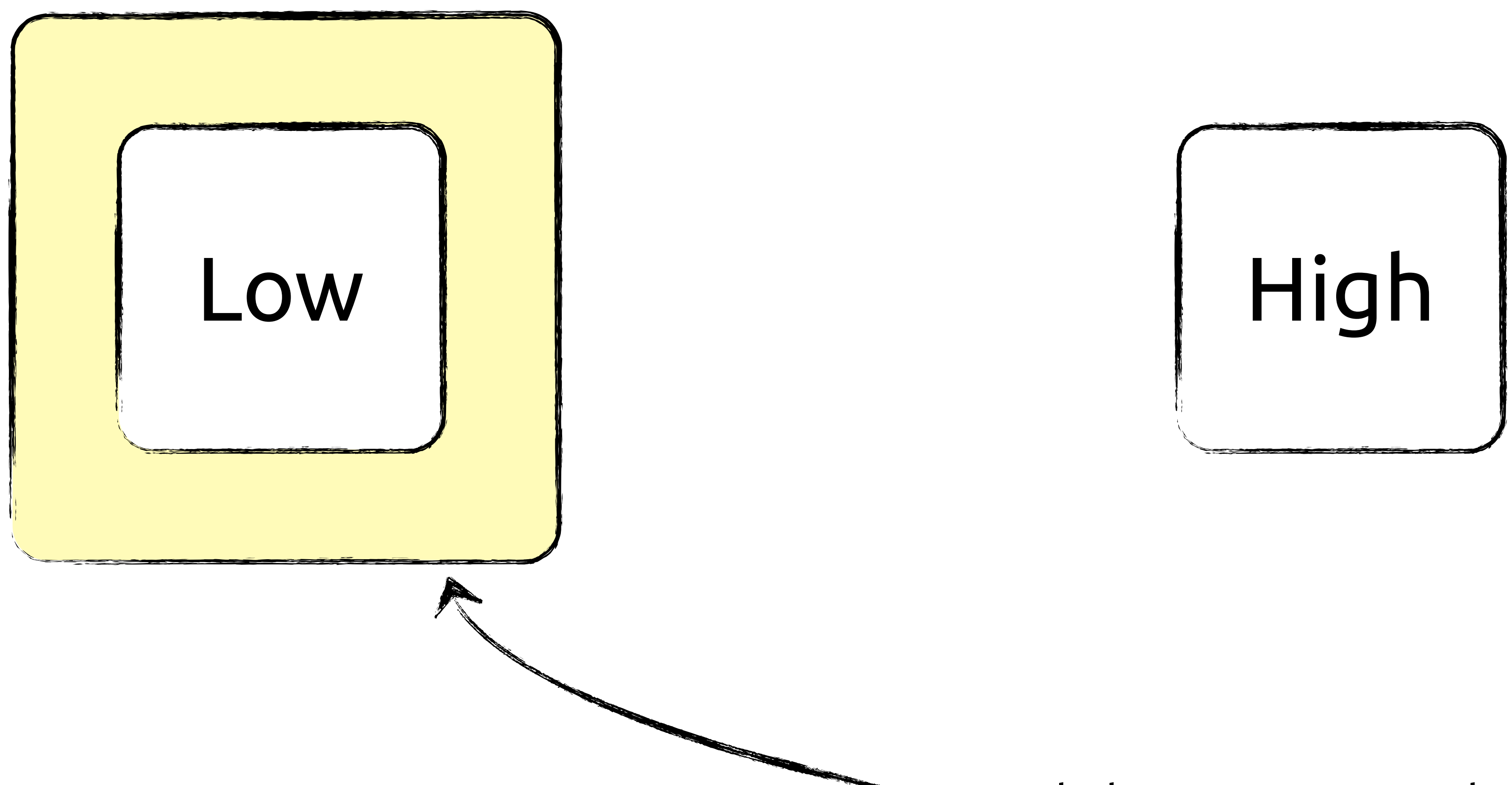
Low

High

Integrating existing languages is problematic

Each language makes tradeoffs,
adding extra complexity

Integrating existing languages is problematic



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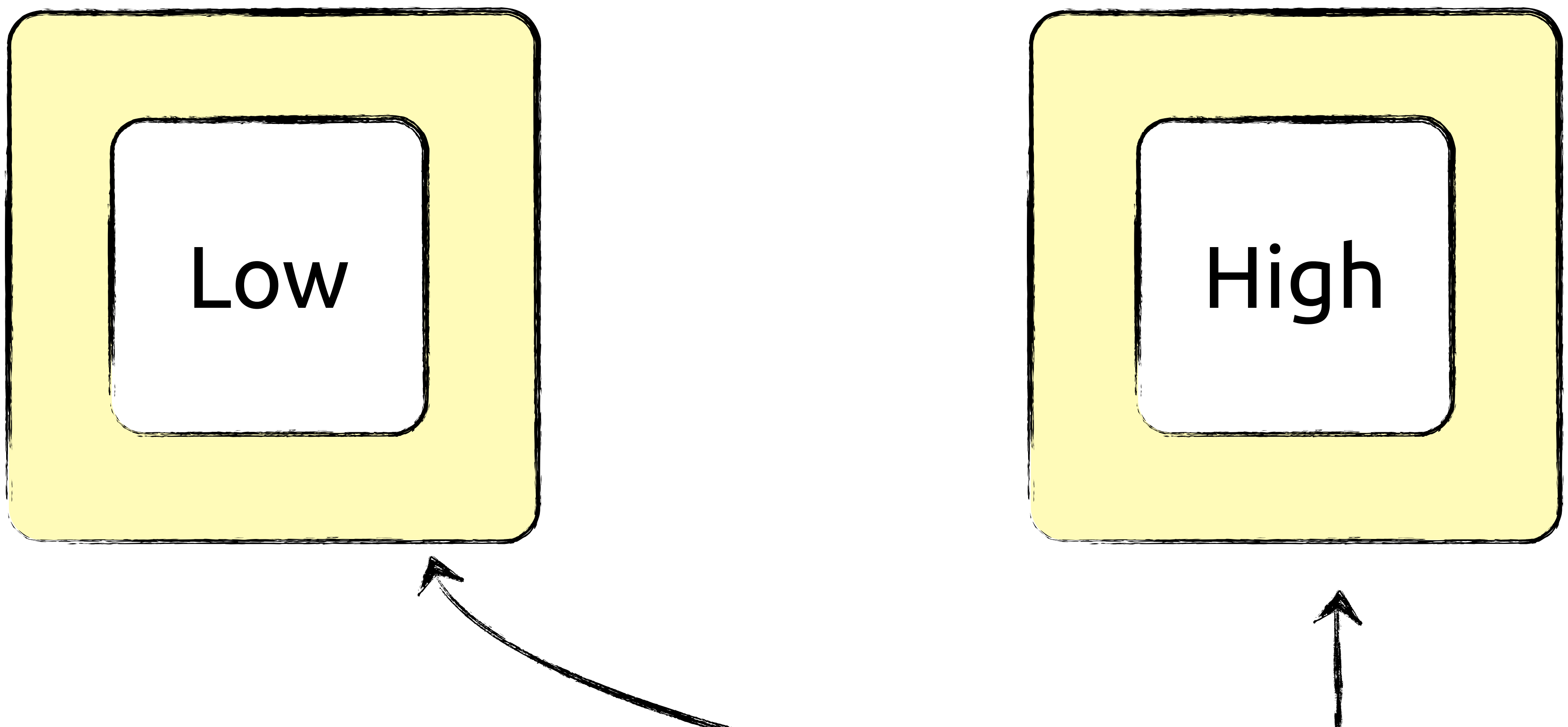

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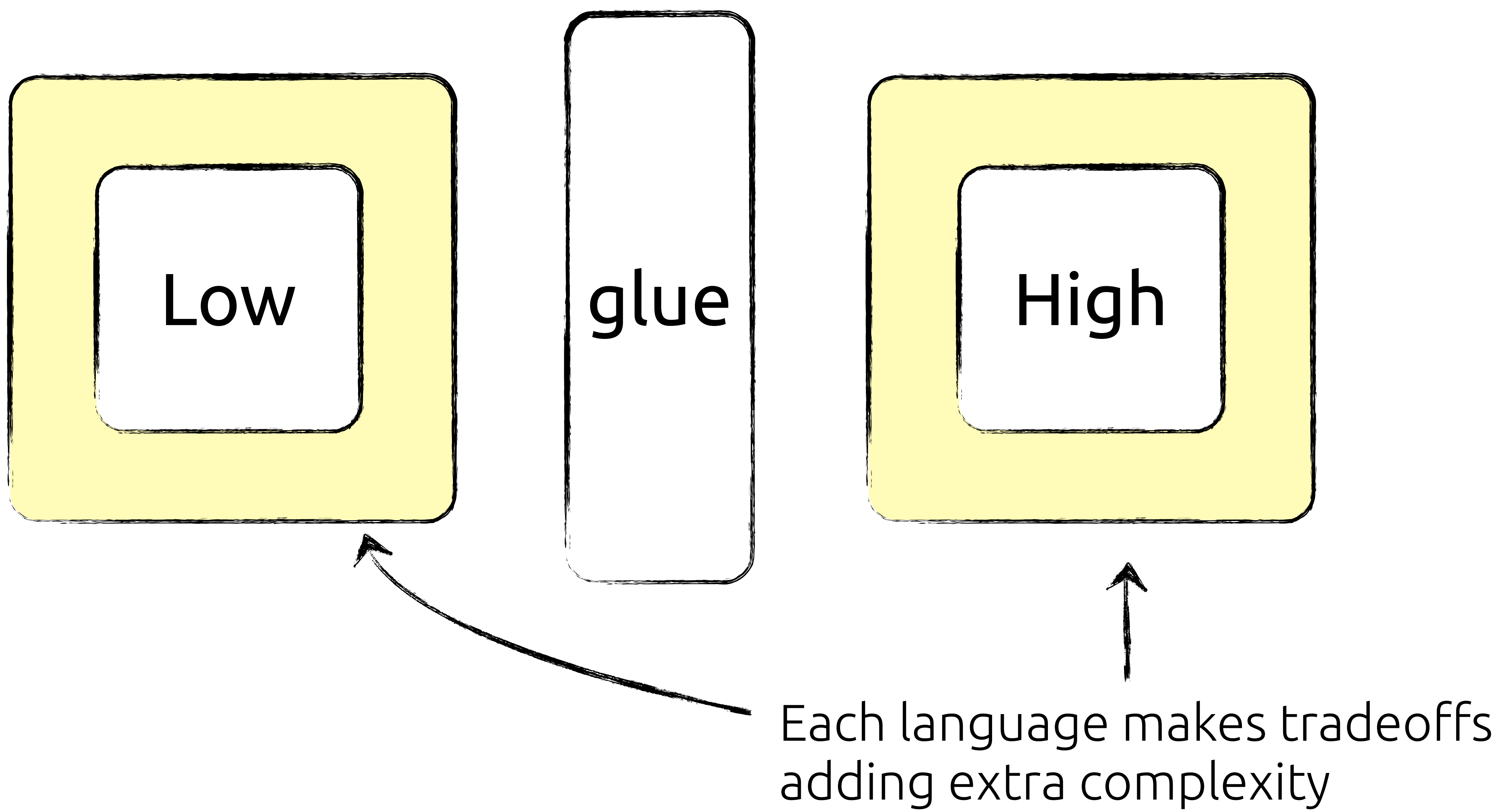
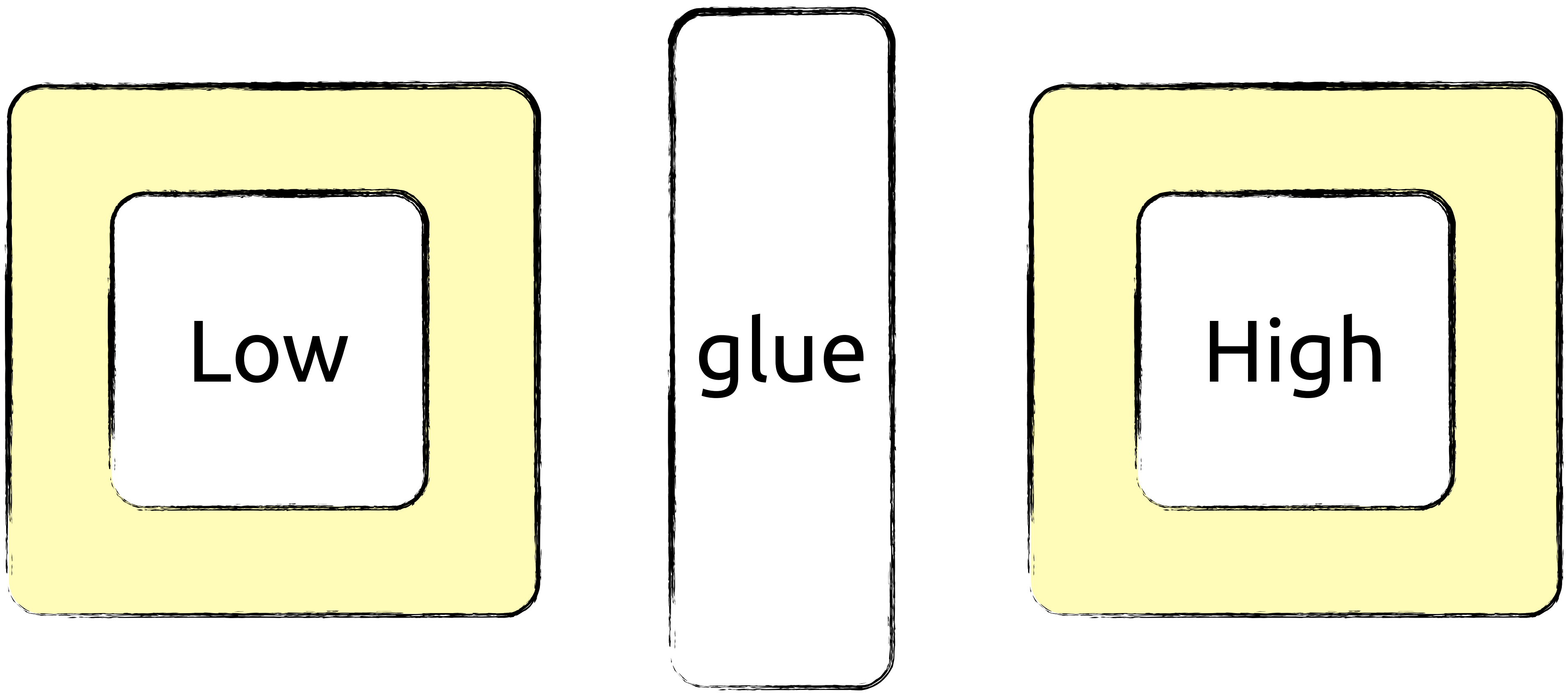


We should design with the expectation of two languages!



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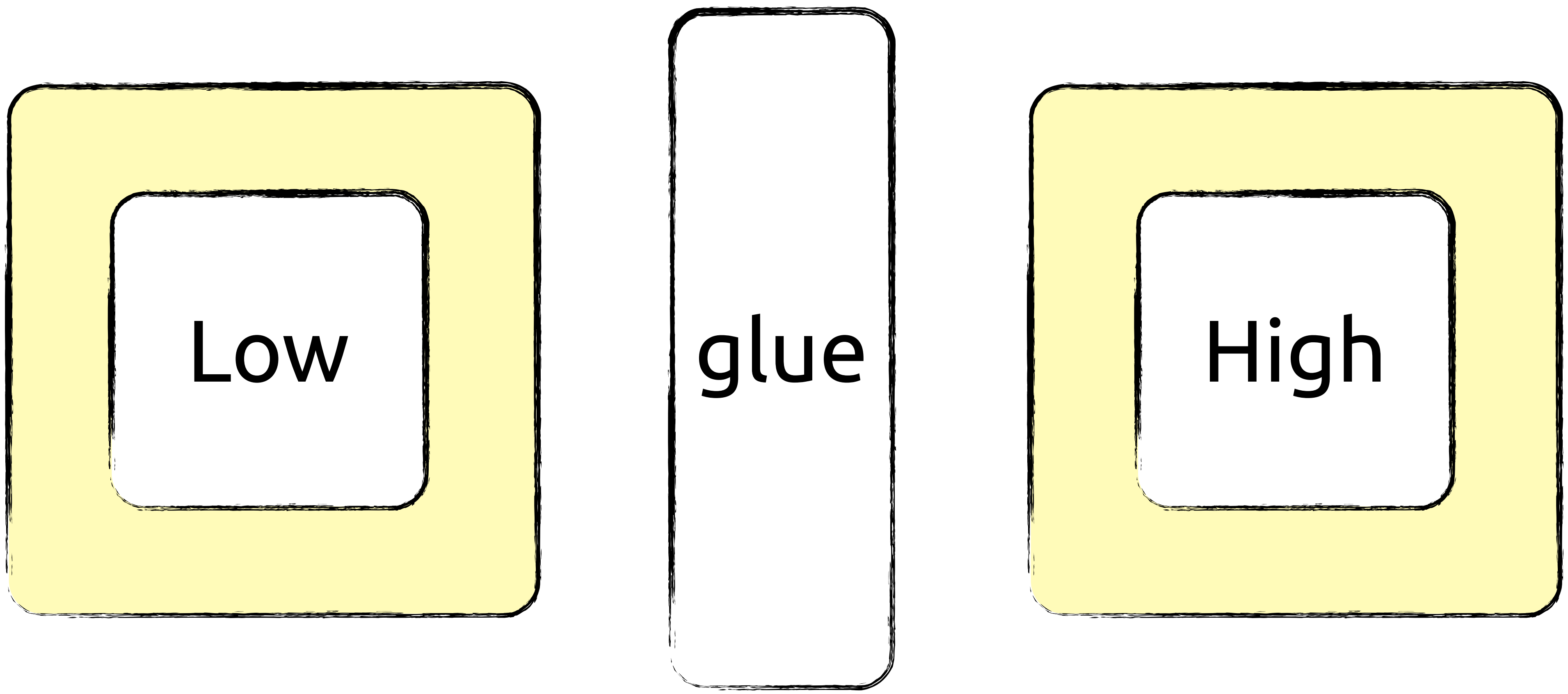

Specialize aggressively
to simplify the languages

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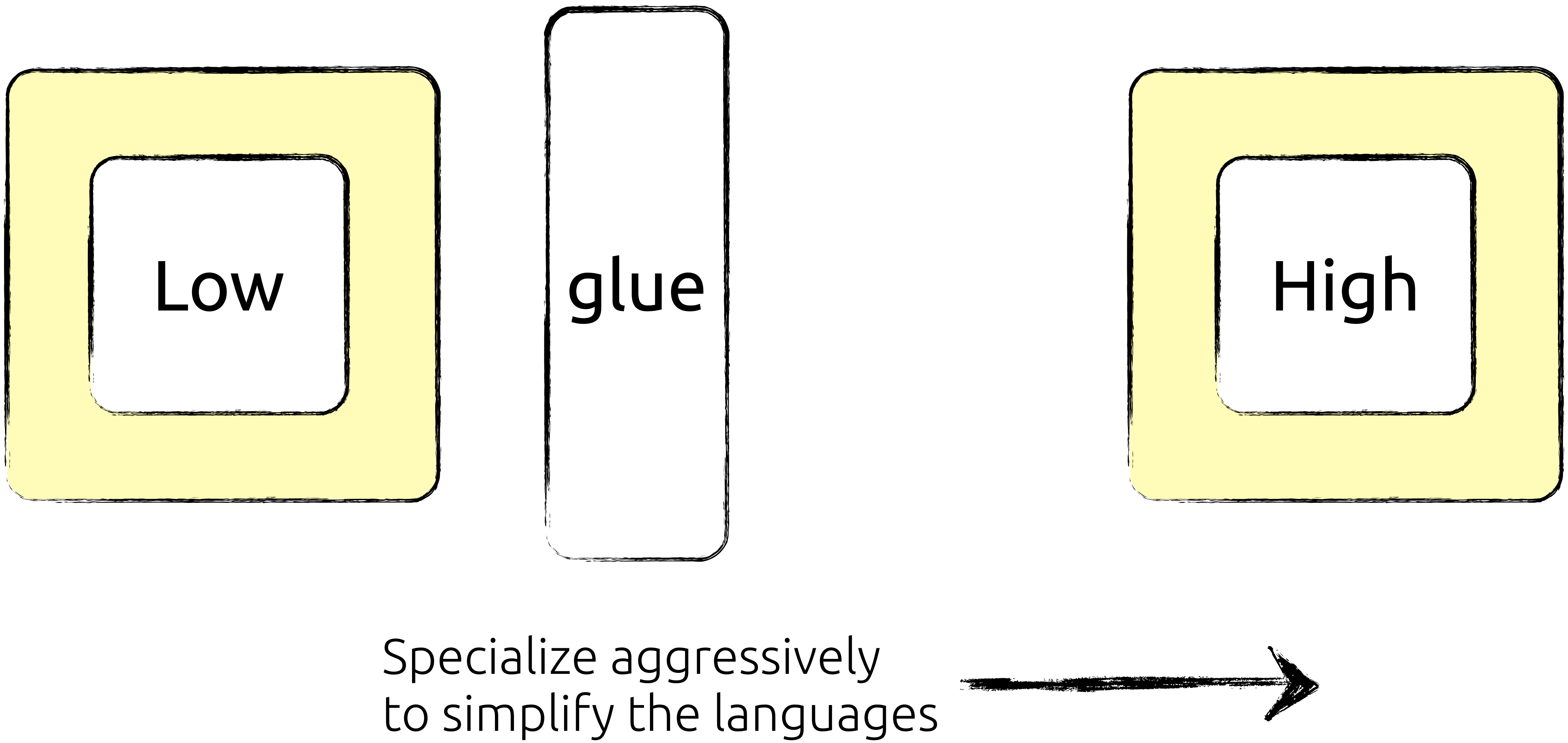

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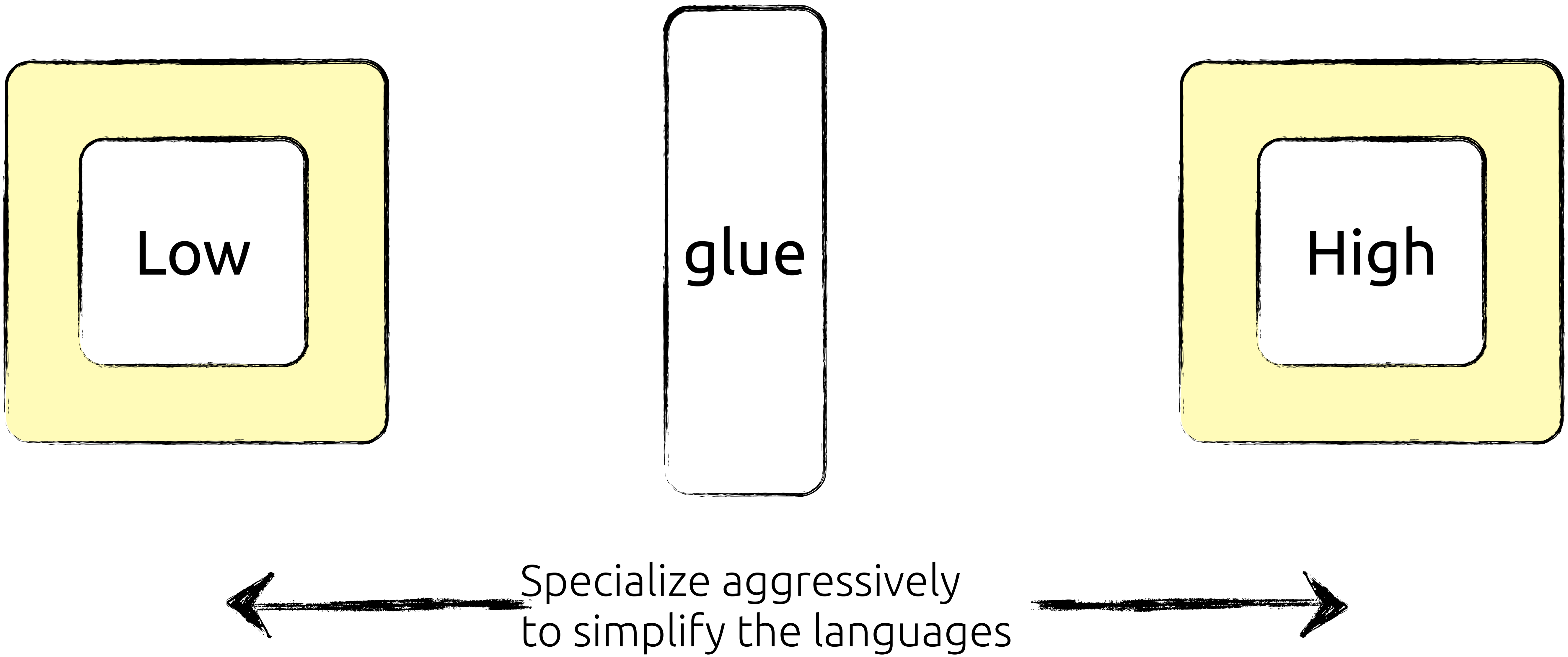

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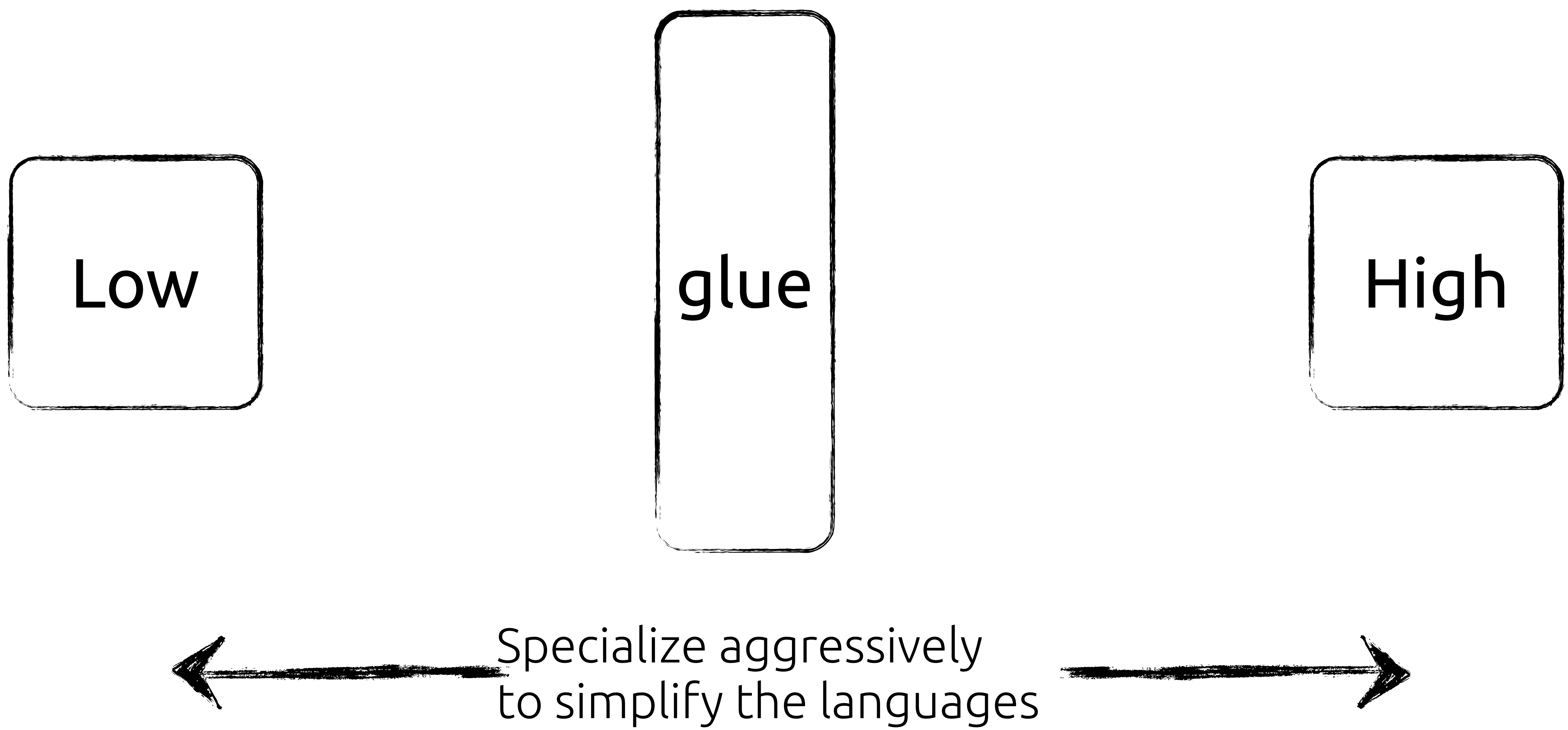
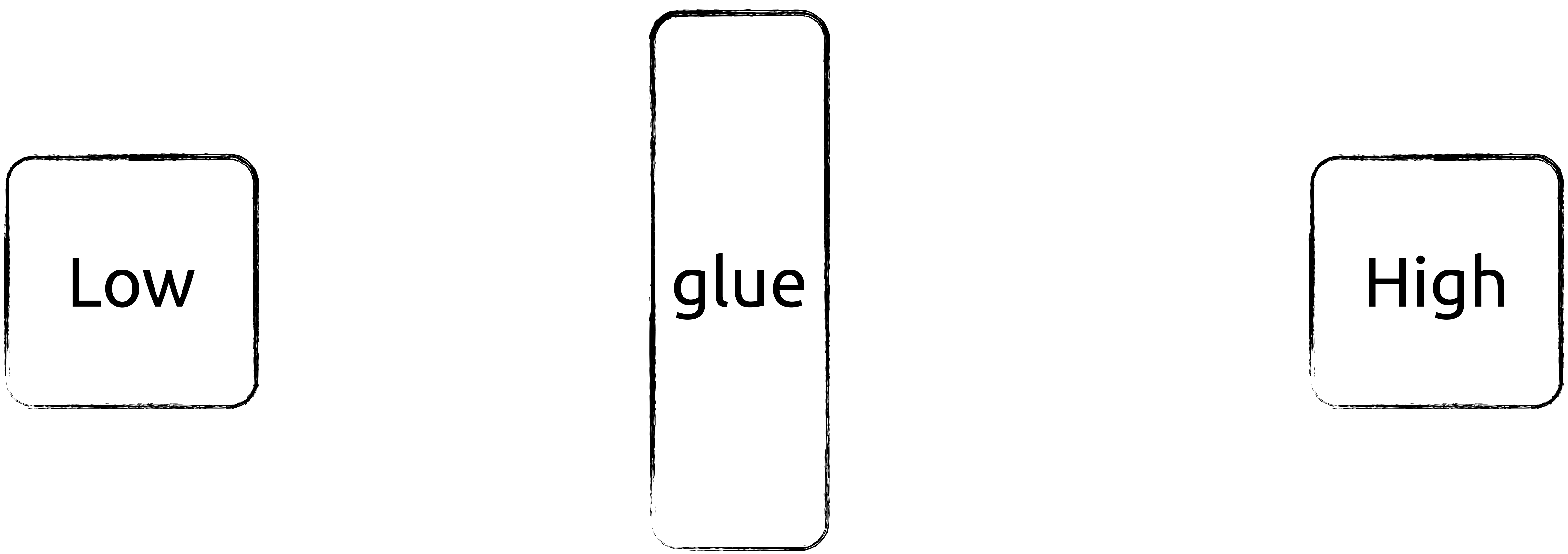
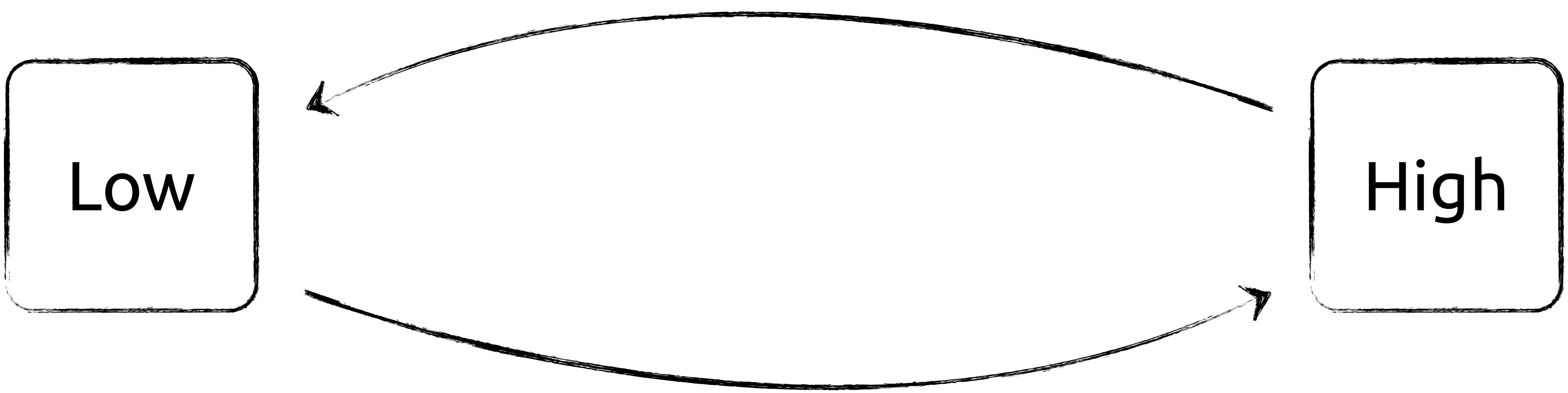


Designing with the expectation of Two Languages



Make each language aware of the other to remove glue.

Designing with the expectation of Two Languages



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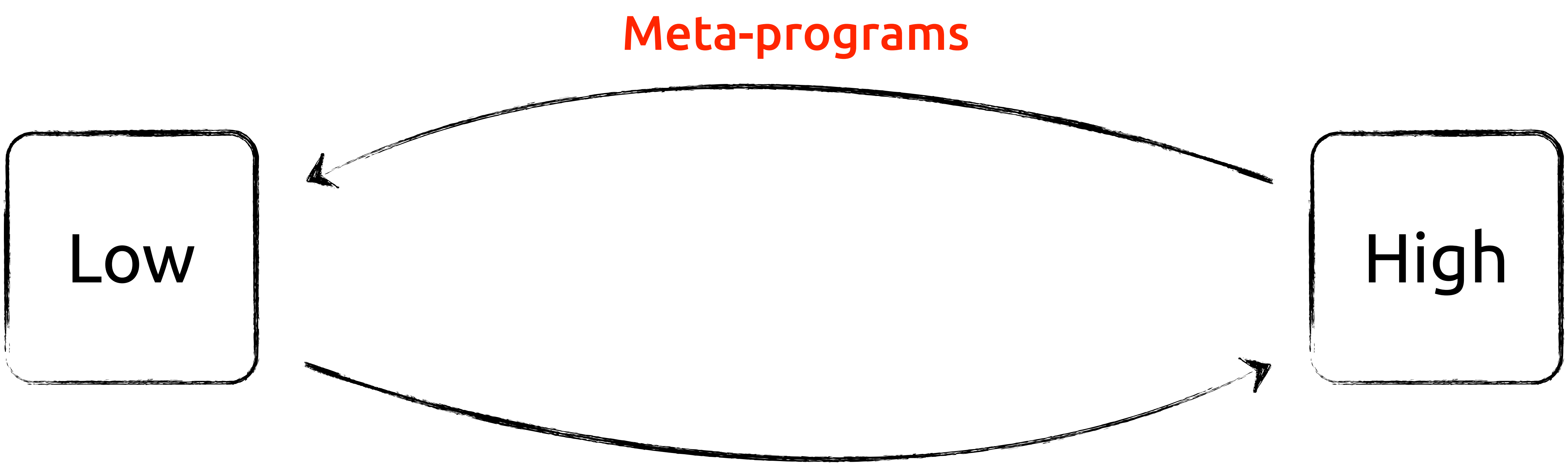
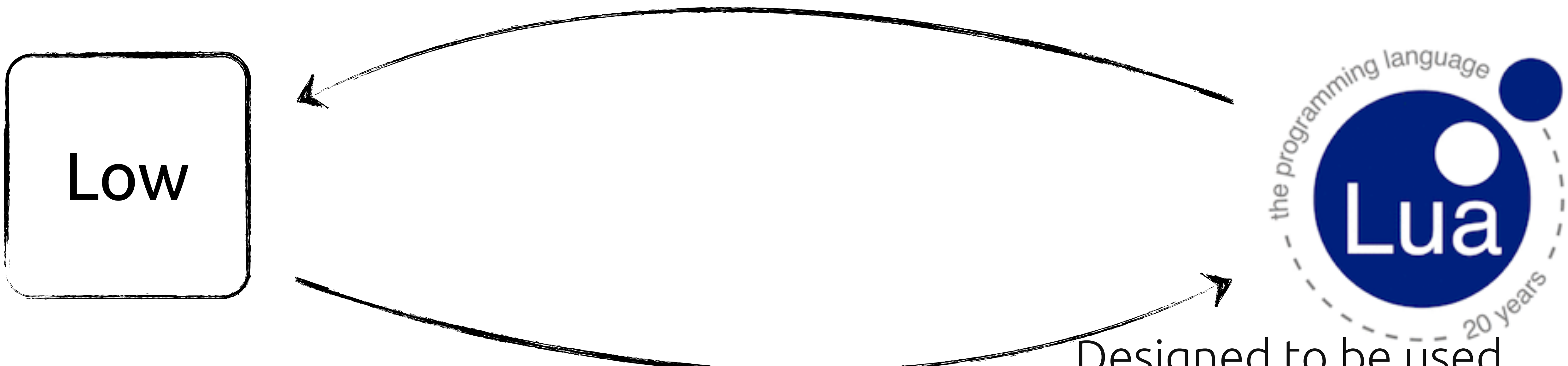
Designing with the expectation of Two Languages



Meta-program the low-level language
to produce high-performance
code from concise descriptions.

Designing with the expectation of Two Languages



Designed to be used with
low-level languages such as C
[Ierusalimschy et al. 11]

Designing with the expectation of Two Languages

New low-level language
designed
to work with high-level
languages

Designed to be used
with
low-level languages such
as C
[Ierusalimschy et al. 11]

Example: Lua

```
--this is a comment.
--top level is Lua code:
function add(a,b)
    return a + b
end
print(add(3,4)) --7
```

Example: Lua + Terra

```
--this is a comment.
--top level is Lua code:
function add(a,b)
    return a + b
end
print(add(3,4)) --7

--terra introduces a low-level terra function
terra addt(a : int, b : int) : int
    return a + b
end

print(addt(3,4)) --7
```

Terra function called from Lua

Types and semantics are similar to C

```
struct FloatArray {
    data: &float;
    N : int;
}

--get an element from the array
terra FloatArray:get(i : int) : float
   return self.data[i]
end
```

Types and semantics are similar to C

Aggregate type

```
struct FloatArray {
    data: &float;
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}


--get an element from the array
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terra FloatArray:get(i : int) : float
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```

Method declaration (sugar)

Terra’s Design

Compartmentalized Runtimes

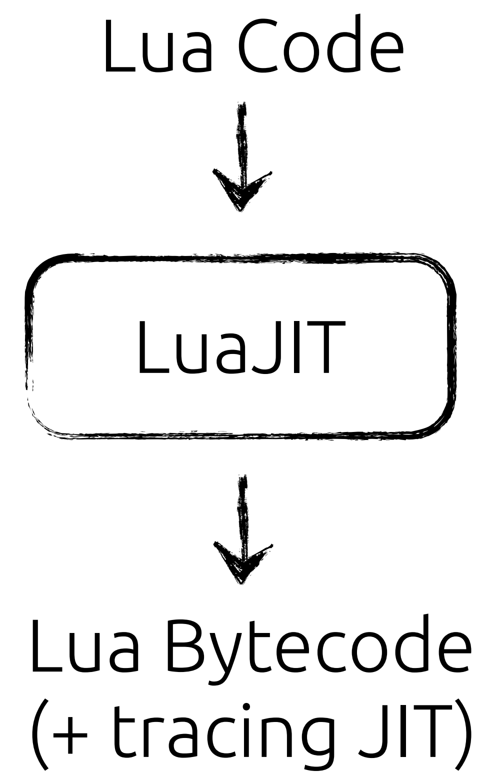
Terra Runtime

Lua Runtime

Compartmentalized Runtimes

Terra Runtime

Lua Runtime



Compartmentalized Runtimes

Terra Runtime

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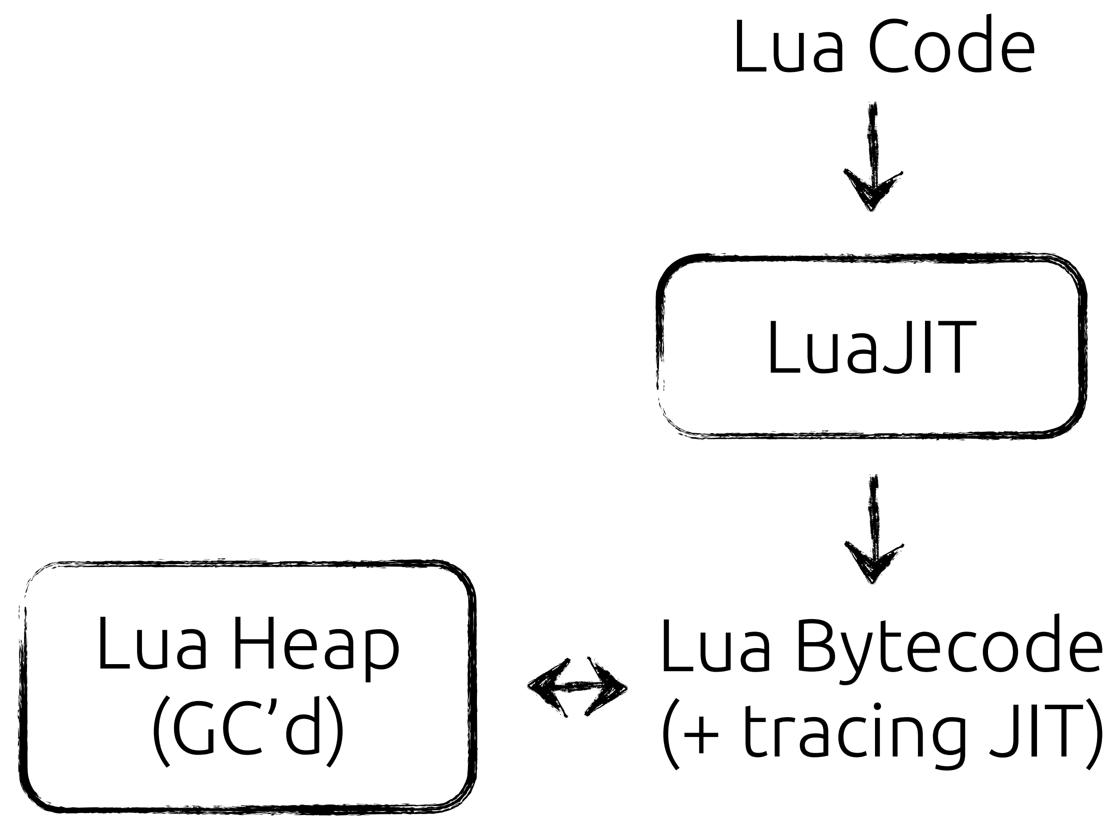
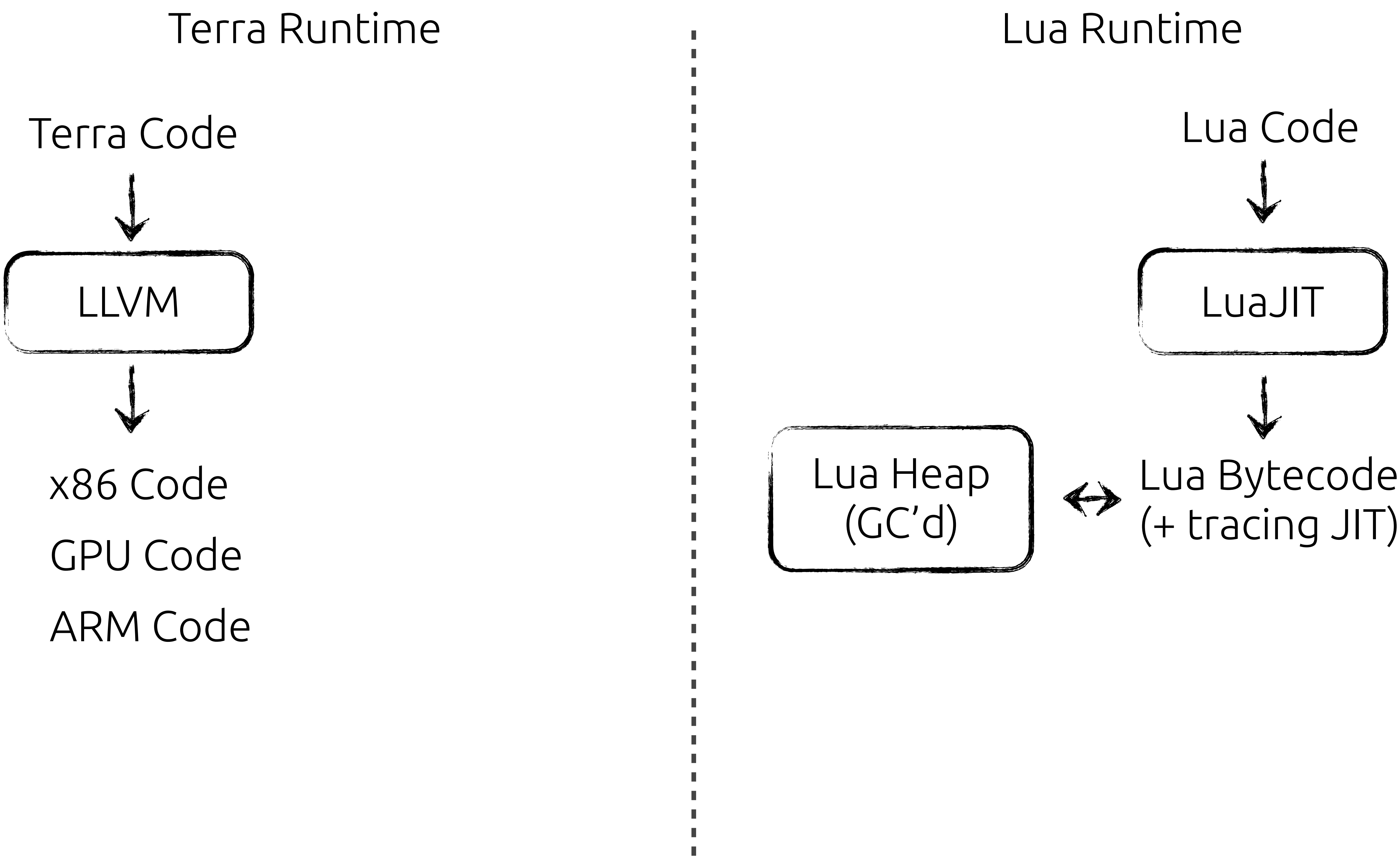


Compartmentalized Runtimes



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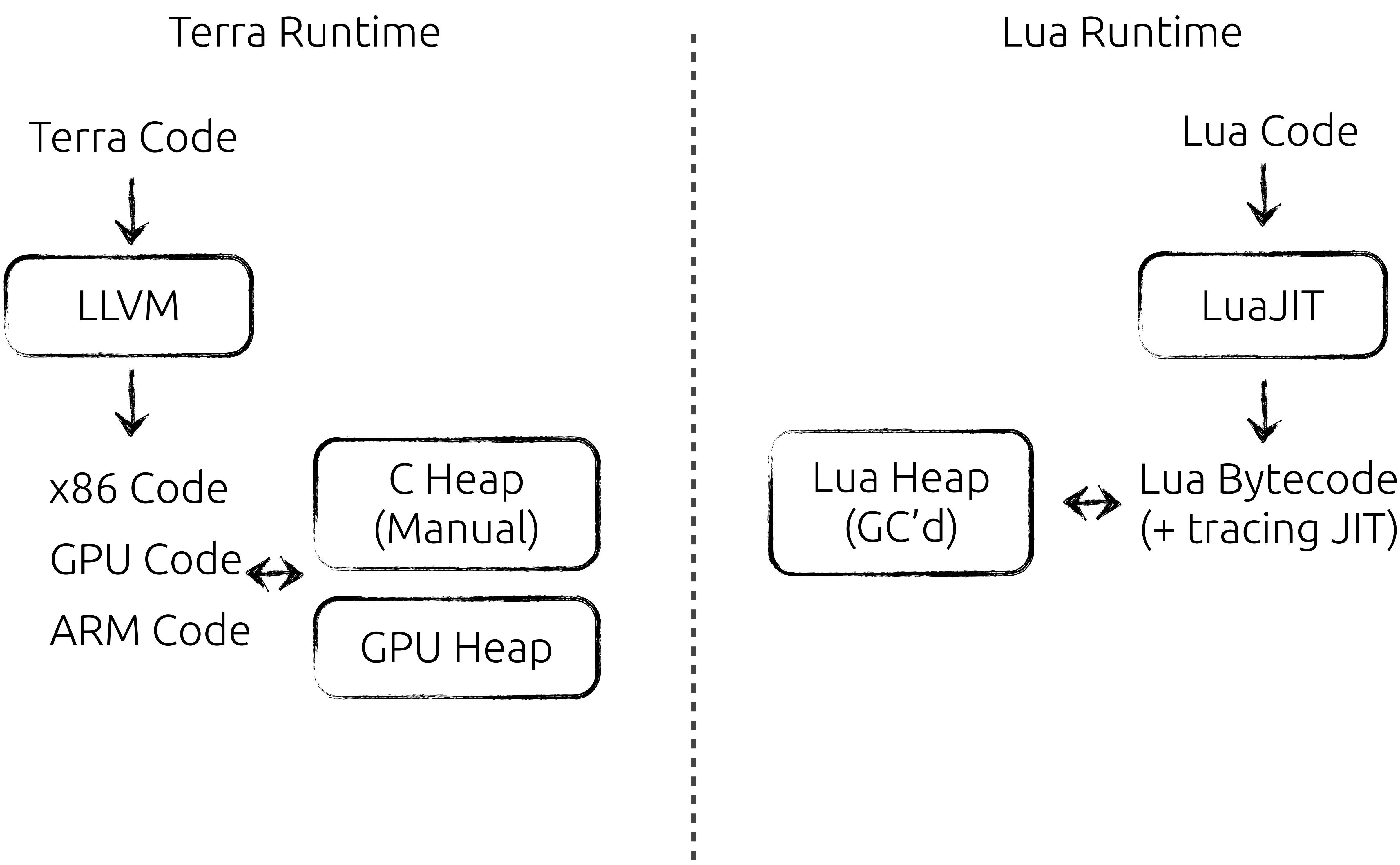

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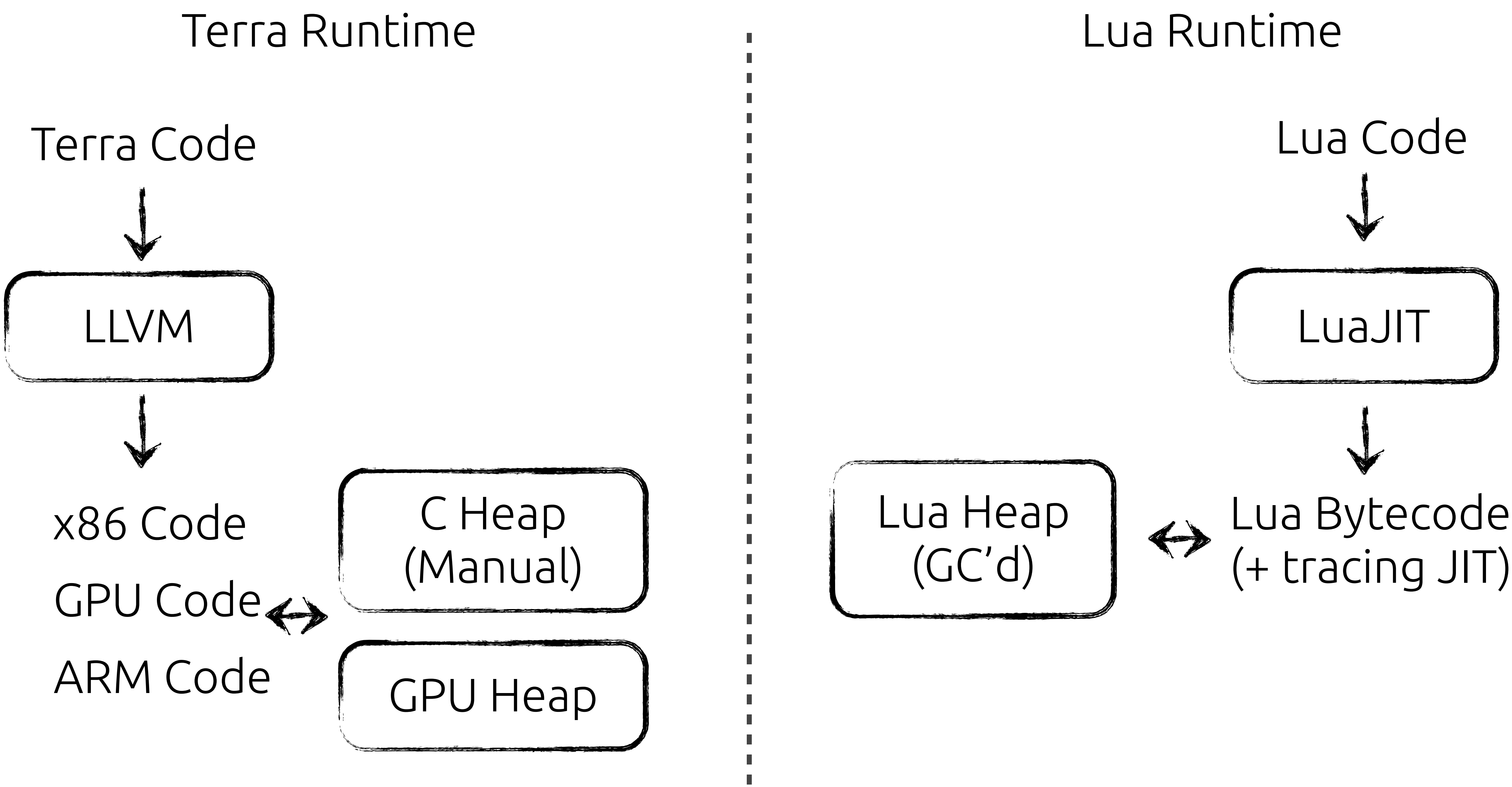

Separation ensures Terra can always produce fast code.

Clean interface between languages

Clean interface between languages

```
terra addt(a : int, b : int) : int
```

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terra addt(a : int, b : int) : int
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Terra functions are first class Lua values:

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Terra functions are first class Lua values:

```
print(addt)
```

Clean interface between languages

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Terra functions are first class Lua values:

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> <terra function>
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Terra functions are first class Lua values:

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Terra uses Lua's lexical environment to resolve symbols:

Clean interface between languages

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Terra functions are first class Lua values:

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```

Terra uses Lua's lexical environment to resolve symbols:

```
terra add1(a : int) : int
```

Clean interface between languages

```
terra addt(a : int, b : int) : int
    return a + b
end
```

Terra functions are first class Lua values:

```
print(addt)
> <terra function>
```

Terra uses Lua's lexical environment to resolve symbols:

```
terra add1(a : int) : int
   return addt(a,1)
```

Clean interface between languages

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terra addt(a : int, b : int) : int
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When called from one another, values are translated from one language

Clean interface between languages

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Terra uses Lua's lexical environment to resolve symbols:

```
terra add1(a : int) : int
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end
```

When called from one another, values are translated from one language to another using rules adapted from LuaJIT's FFI

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```
print(addt(1,2)) -- on call: lua number -> int
```

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> <terra function>
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When called from one another, values are translated from one language to another using rules adapted from LuaJIT's FFI

```
print(addt(1,2)) -- on call: lua number -> int
                 -- on return: number -> int
```

Meta-programming

All Terra entities (types, functions, expressions, symbols) are first-class Lua values.

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Ex. Templating:

```
local struct ArrayType {
  data : &float;
  N : int;
}
terra ArrayType:get(i: int) : float
  return self.data[i]
end
```

Meta-programming

All Terra entities (types, functions, expressions, symbols) are first-class Lua values.

Ex. Templating:

```
local struct ArrayType {
  data : &ElemType;
  N : int;
}
terra ArrayType:get(i: int) : ElemType
  return self.data[i]
end
```

Meta-programming

All Terra entities (types, functions, expressions, symbols) are first-class Lua values.

Ex. Templating:

```
function Array(ElemType)
  local struct ArrayType {
    data : &ElemType;
    N : int;
  }
  terra ArrayType:get(i: int) : ElemType
    return self.data[i]
  end
  return ArrayType
end
FloatArray = Array(float)
```

Terra is meta-programmed from Lua using
multi-stage programming (e.g., from MetaOCaml)

```
function gen_square(x)
  return `x * x
end
```

```
terra mse(a: float, b: float)
  return [gen_square(a)] - [gen_square(b)]
end
```

Terra is meta-programmed from Lua using **multi-stage programming** (e.g., from MetaOCaml)

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function gen_square(x)
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In Lua, a **quotation** creates a Terra expression.

Like a `"string literal"` for code.

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Like a `“string literal”` for code.

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terra mse(a: float, b: float)
  return [gen_square(a)] - [gen_square(b)]
end
```

In Terra, an **escape** splices the value of a Lua expression into Terra code.

Like a string interpolation operator `“hello, %s”`

Evaluation Semantics

```
print(“lua execution”)

function gen_square(x)
  return `x * x
end



terra sqd(a: float, b: float)
  return [gen_square(a)] - [gen_square(b)]
end


print(mse(3,2))
```

Evaluation Semantics

```
print("lua execution")
> lua execution
function gen_square(x)
  return `x * x
end
```

1. Lua code **evaluates** normally until it reaches a Terra function or quote expression

```
terra sqd(a: float, b: float)
  return [gen_square(a)] - [gen_square(b)]
end
```

```
print(mse(3,2))
```

Evaluation Semantics

```
print("lua execution")
> lua execution
function gen_square(x)
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1. Lua code **evaluates** normally until it reaches a Terra function or quote expression

2. The Terra expression is **specialized**, by evaluating all *escaped* Lua expressions.

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terra sqd(a: float, b: float)
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  return [        `a * a ] - [gen_square(b)]
end


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Evaluation Semantics

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print(mse(3,2))
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1. Lua code **evaluates** normally until it reaches a Terra function or quote expression

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3. The Terra function is **evaluated as Terra**

Evaluation Semantics

```
print("lua execution")

function gen_square(x)
  return `x * x
end

terra sqd(a: float, b: float)
  return          a * a    -     b * b
end

print(mse(3,2))
> 5
```

1. Lua code **evaluates** normally until it reaches a Terra function or quote expression

2. The Terra expression is **specialized**, by evaluating all *escaped* Lua expressions.

3. The Terra function is **evaluated as Terra**

Backwards compatibility with C

```
local C = terralib.includec("stdio.h")
-- or for more than one header:
local C = terralib.includecstring [[
#include<stdio.h>
#include<stdlib.h>
]]

-- C is now a Lua table of Terra wrapper functions
-- for each C function:
C.printf("hello, world\n") -- Terra called from Lua
terra hello()
  C.printf("hello, world\n") -- Terra called from Terra
end
```

Try to put all of your C includes into one call because each call is very expensive since it spins up a C compiler.

Pointers and using C's heap

```
var a : int = 1
var pa : &int = &a
@pa = 4
var b = @pa
var b2 = pa[0] -- same
```

```
-- To allocate data in Terra, use C's malloc:
C = terralib.includec("stdlib.h")
terra doit()
    var a = [&int](C.malloc(sizeof(int) * 2))
    @a,@(a+1) = 1,2
    a[0] = 1 -- syntax sugar
end
```

`void*` in C is equivalent to `&opaque` in Terra

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end
```

A cast

`void*` in C is equivalent to **&opaque** in Terra

Back to our image processing example

```
local r =   (a + a:shift(-1,0)
               + a:shift(0,1)
               + a:shift(0,-1)
               + a:shift(1,0)) / 5.0
```

Allocate data using Terra types rather than Lua

Even when using Lua, you can create handles to Terra types. These are usually called "cdata" in plain LuaJIT. (http://luajit.org/ext_ffi.html)

```
local function alloc_image_data(w,h)
    local data = C.malloc(3*w*h)
    return terralib.cast(&uint8,data)
end
local function loadppm(filename)
    ...
    local data = alloc_image_data(image.width,image.height)
    for i = 0,image.width*image.height - 1 do
        data[3*i],data[3*i+1],data[3*i+2] =
           parseNumber(),parseNumber(),parseNumber()
    end
    ...
end
```

Using an intermediate representation

Lua data structure that represents the computation we want to do:

```
(a + a:shift(1,0))/2

-- use operator overload to build the table
-- 'result'
local load_a = { kind = "load", data = <cdata> }
local shift = { kind = "shift", value = load,
                sx = 1, sy = 0 }
local add = { kind = "+", lhs = load_a, rhs = shift }
local const = { kind = "const", value = 2 }
local div = { kind = "/", lhs = add, const }
```

Building Our IR

Each image object internally tracks its IR

```
function image:shift(sx,sy)
    local width,height = self.width,self.height
    local result = image.new(width,height)
    result.tree = { kind = "shift", sx = sx, sy = sy,
                    value = self.tree }
    return result
end
```

Making an Image

A function turns an image represented by IR into a concrete ‘reified’ image:

```
function image:reify()
    local result = image.new(self.width,self.height)
    result.tree = { kind = "load",
                    data = alloc_image_data(self.width,self.height)
                  }

    local compiled_function =
       compile_image_ir(self.width,self.height,self.tree)

    compiled_function(result.tree.data)
    return result
end
```

Compiling our Image IR

```
local function compile_image_ir(W,H,tree)
    local function gen_tree(tree,x,y,c)
        ...
    end
    local terra body(data : &uint8)
        for y = 0,H do
          for x = 0,W do
            for c = 0,3 do
              data[3*(y*W + x) + c] = [ gen_tree(tree,x,y,c) ]
            end
          end
        end
    end
    return body
end
```

```
-- a helper function
local terra load_data(data : &uint8, x: int, y: int, c: int): float
    if x < 0 or x >= W and y < 0 or y >= H then
        return 0.f
    end
    return data[3*(y*W + x) + c]
end
```

```
-- a helper function
local terra load_data(data : &uint8, x: int, y: int, c: int): float
    if x < 0 or x >= W and y < 0 or y >= H then
        return 0.f
    end
    return data[3*(y*W + x) + c]
end

local function gen_tree(tree,x,y,c)
    if tree.kind == "const" then
        return `float(tree.value)
    elseif tree.kind == "load" then
        return `load_data(tree.data,x,y,c)
    elseif tree.kind == "+" then
        local lhs = gen_tree(tree.lhs,x,y,c)
        local rhs = gen_tree(tree.rhs,x,y,c)
        return `lhs + rhs
    ...
    elseif tree.kind == "shift" then
        local xn,yn = `x + tree.sx,`y + tree.sy
        return gen_tree(tree.value,xn,yn,c)
    end
end
```

Results

Our Lua implementation: 0.27 MP/s

Naive C loop doing the same thing: **48.2 MP/s**

Our Terra loop: **39.1 MP/s**

(Still slower by a bit because the C loop was smarter about bounds checking.)

Results

Our Lua implementation: 0.27 MP/s

Naive C loop doing the same thing: **48.2 MP/s**

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(Still slower by a bit because the C loop was smarter about bounds checking.)

Question: how can we do better?

Terra in Details

Resources for learning Terra

terralang.org

- Getting Started Guide
- API reference (includes more detailed descriptions)
- Research papers

Meta-programming Details

Quotations:

```
local short_quote = `3 + 4 --only an expression
local long_quote = quote -- can include expressions
                     C.printf("hi\n")
                     var a = 4
                   in 3 + a end
```

Escapes:

```
terra my_function()
  -- short escape
  var a = [ short_quote ]
  escape -- long escape
    for i = 1,10 do
      emit quote
         C.printf("hi %d",[i])
      end
    end
  end
end
```

Meta-program Anything

Multiple Expressions:

```
local short_quotes = {`3 + 4,`5+6 }
terra returntwo()
  a_function_with_two_arguments(short_quotes) -- pastes both
  return short_quotes -- returns both as a tuple
end
```

Multiple Statements:

```
local hi = quote C.printf("hi\n") end
local stuff = {hi,hi}
terra chatty()
  [hi]
end
```

Meta-program Anything

Use a variable before the quote that defines it:

```
local a = symbol(int,"a") -- type and name are optional
local addone = quote
  a = a + 1
end
terra useit()
  var [a] = 0 -- don't make new 'a', define the symbol a
  [addone]
  return a -- 1
end
```

Multiple arguments to a function:

```
local args = { symbol(), symbol(), symbol()}

terra useit(another_arg : int, [args])
  return another_arg + [args[1]] + [args[2]] + [args[3]]
end
```

Meta-program Anything

Field and method names:

```
struct Complex {
  real : float
  imag : float
}
-- or, via meta-programming:
local entries = { {“real”, float}, {“imag”, float} }
Complex = terralib.types.newstruct(“Complex”)
Complex.entries = entries

terra Complex:add(rhs : Complex) : Complex
    return {self.real + rhs.real, self.imag + rhs.imag}
end

local string_add,string_imag = “add”,”imag”
terra use_complex(c : Complex)
  var c2 = c:[string_add](c)
  return c2.[string_imag]
end
```

Variables

This is actually a Lua expression

```
local myluavalue = 6
terra foo()
  var b : float = 1.f -- type explicitly specified
  var a = 1.0 -- double type inferred from RHS
  var c : int, d = 3,4
  var d = myluavalue -- myluavalue is constant
end

-- Globally accessible Terra variable
local myglobal = global(int,3)
terra setglobal()
   myglobal = 4
end
terra getglobal()
  return myglobal
end
```

Most of the time, you will not need to use global variables.
Instead Terra objects can be store in Lua values and passed as arguments when necessary.

Control Flow: If

Must be booleans

```
if a or b and not c then
    C.printf("then\n")
elseif c then
    C.printf("elseif\n")
else
    C.printf("else\n")
end
```

Loops

```
var a = 0
while a < 10 do
    C.printf("loop\n")
    a = a + 1
end

repeat
    a = a - 1
    C.printf("loop2\n")
until a == 0

while a < 10 do
    if a == 8 then
        break
    end
    a = a + 1
end
```

For

0-indexed language so for-loop is not inclusive of upper bound

```
for i = 0,10 do
    C.printf("%d\n",i)
end

for i = 0,10,2 do
    c.printf("%d\n",i) --0, 2, 4, ...
end
```

Gotos

```
::loop::
C.printf("y\n")
goto loop
```

Almost exclusively used for when *generating code* for things that do not have structured control flow.

Functions: Multiple Returns in Terra

```
terra sort2(a : int, b : int) : {int,int}
    if a < b then
        return a, b
    else
        return b, a
    end
end

terra doit()
    -- the multiple returns are returned
    -- in a 'tuple' of type {int,int}:
    var ab : {int,int} = sort2(4,3)
    -- tuples can be pattern matched,
    -- splitting them into separate variables
    var a : int, b : int = sort2(4,3)
    --now a == 3, b == 4
end
doit()
```

Functions: Mutual Recursion

When a Terra function is created it needs to know about all the identifiers it references:

```
terra isodd -- declare isodd as a Terra function
terra iseven(n : uint32)
    if n == 0 then
        return true
    else
      -- OK! isodd is declared
        return isodd(n - 1)
    end
end
and terra isodd(n : uint32)
    if n == 0 then
        return false
    else
        return iseven(n - 1)
    end
end
```

Primitive Types

- Integers: `int int8 int16 int32 int64`
- Unsigned integers: `uint uint8 uint16 uint32 uint64`
- Boolean: `bool`
- Floating Point: `float double`

Primitive Operators

- Arithmetic: `- + * / %`
- Comparison: `< <= > >= == ~=`
- Logical: `and or not`
- Bitwise: `and or not ^ << >>`

```
true and false --Lazily evaluated logical and
1 and 3        --Eagerly evaluated bitwise and
```

Function Pointers

```
terra add(a : int, b : int) return a + b end
terra sub(a : int, b : int) return a - b end
terra doit(usesub : bool, v : int)
    var a : {int,int} -> int
    if usesub then
        a = sub
    else
        a = add
    end
    return a(v,v)
end
```

Fixed Length Arrays

```
var a : int[4]
a[0],a[1],a[2],a[3] = 0,1,2,3
var a = array(1,2,3,4) -- a has type int[4]
var a = arrayof(int,3,4.5,4) -- a has type int[3]
                                 -- 4.5 will be cast to an int
```

Vectors

```
terra saxpy(a :float,  X : vector(float,3), Y : vector(float,3),)
   return a*X + Y
end

var a = vector(1,2,3,4) -- a has type vector(int,4)
var a = vectorof(int,3,4.5,4) -- a has type vector(int,3)
                                  -- 4.5 will be cast to an int
```

Structs

Only user-defined data type.

Analog in Terra to Lua's tables.

```
struct Complex {
  real : float
  imag : float
}
terra doit()
    var c : Complex
    c.real = 4
    c.imag = 5
end
```

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Analog in Terra to Lua's tables.

```
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  real : float
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}
terra doit()
    var c : Complex
    c.real = 4
    c.imag = 5
end
```

```
struct B -- declaration
struct A {
  b : &B
}
struct B {
  a : &A
}
```

There is no -> Operator

```
terra doit(c : Complex)
    var pc = &c
    return pc.real --sugar for (@pc).real
end
```

Syntax Sugar for Struct Creation

```
-- a pair of floats
var a : tuple(float,float) = {3.f, 4.f}

-- an anonymous struct
var b = { real = 3.0, imag = 2.0 }
var c = Complex(b) -- cast
var d = Complex { real = 3.0, imag = 2.0 } -- also a cast
```

Syntax Sugar for Methods

```
struct Complex { real : double, imag : double }
Complex.methods.add = terra(self : &Complex, rhs : Complex) : Complex
    return {self.real + rhs.real, self.imag + rhs.imag}
end

terra doit()
    var a : Complex, b : Complex = {1,1}, {2,1}
    var c = a:add(b) -- sugar for Complex.methods.a(a,b)
    var ptra = &a
    var d = ptra:add(b) --also works
end

--same as before:
terra Complex:add(rhs : Complex) : Complex
    return {self.real + rhs.real, self.imag + rhs.imag}
end
```

Terra Entities as Lua objects

Since all Terra entities are Lua objects, we can introspect them from Terra:

```
> terra foo() return 4 end
> foo:printpretty() -- use foo:printpretty(false)
                    -- to see debug _before_ typechecking
[string "stdin"]:1:     foo = terra() : int32
                            return 4
                        end
> myquote = `3 + 4
> myquote:printpretty()
[string "stdin"]:1:     3 + 4
> aterratype = &int
> print(aterratype)
&int32
> foo:disas()
assembly for function at address 0x9b50010
0x9b50010(+0):   mov  eax, 4
0x9b50015(+5):   ret
```

Hygiene

Variables are still lexically scoped:

```
function use_quote(q)
  return quote
    var a = false
  in q end
end
terra my_function()
  var a = true
  return [ quote(`a) ] -- returns true
end
```

Casts

Rules for type casts are mostly the same as C, but the syntax is different.

Apply the Terra type object *as a function*:

```
terra todouble(a : int)
  return double(a)
end
```

If you need to use Lua code to get the Type object, you will need to escape the expression

```
terra todoublepointer(a : &opaque)
  return [&double](a)
end
local doublepointer = &double
terra todoublepointer(a : &opaque)
  return doublepointer(a) -- same as above
end
```

Programmatically decide memory layout of types

```
terra example()

  var s : Student
  s:setname("bob")
  s:setyear(4)

end
```

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Like a high-level language: generate types using dynamic information.

Programmatically decide memory layout of types

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  s:setname("bob")
  s:setyear(4)

end
```

```
Student.metamethods.__getentries =
function()
  file = io.open("students.dat","r")

  create ORM by populating type with fields
  described in database file

  return entries
end
```

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```

name: rawstring	year: int

use generated layout in compiler optimizations

Like a high-level language: generate types using dynamic information.
Like a low-level language: optimize code using memory layout.

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end
```

name: rawstring	year: int

use generated layout in compiler optimizations

Object behavior can also be meta-programmed.

Like a high-level language: generate types using dynamic information.
Like a low-level language: optimize code using memory layout.

Using compilers like LLVM to dynamically generate code tedious and verbose

```
float solve(float a, float b, float c) {
  return (-b + sqrt(b*b - 4*a*c)) / (2 * a);
}
```

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float solve(float a, float b, float c) {
  return (-b + sqrt(b*b - 4*a*c)) / (2 * a);
}
```

```
Value* float_mul = B.CreateFMul(float_b, float_b);
Value* float_mul1 = B.CreateFMul(float_a, const_float_3);
Value* float_mul2 = B.CreateFMul(float_mul1, float_c);
Value* float_sub3 = B.CreateFSub(float_mul, float_mul2);
Value* float_call = B.CreateCall(func_sqrtf, float_sub3);
Value* float_add = B.CreateFSub(float_call, float_b)
Value* float_div = B.CreateFMul(float_add, const_float_4);
Value* float_mul4 = B.CreateFMul(float_div, float_a);
B.CreateReturn(float_mul4);
```

Using compilers like LLVM to dynamically generate code tedious and verbose

```
//types

std::vector<Type*> SolveTy_args;
SolveTy_args.push_back(Type::getFloatTy(C));
SolveTy_args.push_back(Type::getFloatTy(C));
SolveTy_args.push_back(Type::getFloatTy(C));
FunctionType* SolveTy = FunctionType::get(Type::getFloatTy(C),SolveTy_args)

std::vector<Type*>SqrtTy_args;
SqrtTy_args.push_back(Type::getFloatTy(C));
FunctionType* SqrtTy = FunctionType::get(Type::getFloatTy(C),SqrtTy_args);

PointerType* PtrSqrtTy = PointerType::get(SqrtTy, 0);

//function declarations

Function* func_solve = Function::Create(SolveTy,
                    GlobalValue::ExternalLinkage,
                    "solve", M);
Function* func_sqrtf = Function::Create(SqrtTy,
                    GlobalValue::ExternalLinkage,
                    "sqrtf", M);

// constants
ConstantFP* const_float_3 = ConstantFP::get(C, 4.f);
ConstantFP* const_float_4 = ConstantFP::get(C, 5.f);

// function definition
Function::arg_iterator args = func_solve->arg_begin();
Value* float_a = args++;
Value* float_b = args++;
Value* float_c = args++;

BasicBlock* label_entry = BasicBlock::Create(C, "entry",func_solve,0);
IRBuilder<> * B(label_entry);
Value* float_mul = B.CreateFMul(float_b, float_b);
Value* float_mul1 = B.CreateFMul(float_a, const_float_3);
Value* float_mul2 = B.CreateFMul(float_mul1, float_c);
Value* float_sub3 = B.CreateFSub(float_mul, float_mul2);
Value* float_call = B.CreateCall(func_sqrtf, float_sub3);
Value* float_add = B.CreateFSub(float_call, float_b)
Value* float_div = B.CreateFMul(float_add, const_float_4);
Value* float_mul4 = B.CreateFMul(float_div, float_a);
B.CreateReturn(float_mul4);
```

```
) {
2 * a);
```