Terra: A Multi-Stage Language for High-Performance Computing

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- Low-level languages(e.g. C) are good: we need to make best use of features of the target architecture(e.g. vector instructions).
- Programming is difficult!
- Solution: use high-level languages to generate low-level languages code(e.g. FFTW: OCaml $\rightarrow$ C).

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- Optimizer: generate plan to guide how to generate code.
- Compiler: generate target code based on the plan.
- Runtime: support the generated code and provide feedback to the optimizer.
- Problem1: Separating compiler and optimizer from the runtime makes it difficult to feed runtime statistics back to the compiler to perform problem-specific optimizations.
- Problem2: How can we re-use legacy libraries?

Two-Language Design

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- Terra code runs independently, to avoid including high-level features.
- Lua's stack-based C API makes it easy to interface with legacy code.

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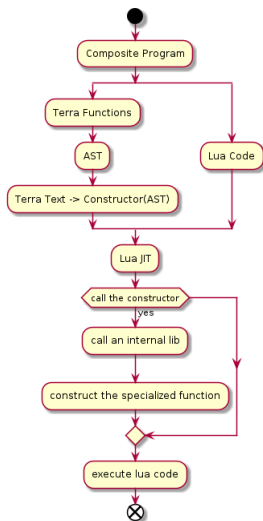
Some Code Examples

```
terra min(a: int, b: int): int
  if a < b then return a
  else return b end
end
struct GreyScaleImage {
  data: &float
  N: int
}
```

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- Terra functions will be executed in LLVM JIT.
- You can dump Terra functions to an object file(i.e. something.o in Linux) if you like.
- Quotation: using brackets([]) for escaping and backtick(expressions)/quote keyword(statements) for creating quotation.

Quotation Example

```
local a = 5
terra sin5()
  return [ math.sin(a) ]
  end
function addtwo(a,b)
  return `a + b
end
local printtwice = quote
  C.printf("hello\n")
  C.printf("hello\n")
  end
```

It Just Works!

```
-- C++                          |  -- Lua/Terra
int add(int a, int b) {         |  terra add(a : int,b : int) : int
    return a + b;               |      return a + b
}                               |  end
                                |
                                |  -- Conditional compilation is done
                                |  -- with  control-flow that
                                |  -- determines what code is defined
#ifdef _WIN32                   |  if iswindows() then
void waitatend() {              |      terra waitatend()
    getchar();                  |          C.getchar()
}                               |      end
#else                           |  else
void waitatend() {}             |      terra waitatend() end
#endif                          |  end
                                |
                                |  -- Templates become Lua functions
                                |  -- that take a terra type T and
                                |  -- use it to generate new types
                                |  -- and code
template<class T>               |  function Array(T)
struct Array {                  |      struct Array {
    int N;                      |          N : int
    T* data;                    |          data : &T
                                |      }
    T get(int i) {              |      terra Array:get(i : int)
        return data[i];         |          return self.data[i]
    }                           |      end
                                |      return Array
};                              |  end
typedef                         |
Array<float> FloatArray;        |  FloatArray = Array(float)
```

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- e.g. block the loop nests to make the memory access more friendly to the cache.

A Simple Filter Example

```
GreyscaleImage = Image(float)
terra laplace(img: &GreyscaleImage,
out: &GreyscaleImage) : {}
  --shrink result, do not calculate boundaries
  var newN = img.N - 2
  out:init(newN)
  for i = 0,newN do
    for j = 0,newN do
      var v = -img:get(i+0,j+1) - img:get(i+2,j+1)
      - img:get(i+1,j+2) - img:get(i+1,j+0)
      + 4 * img:get(i+1,j+1)
      out:set(i,j,v)
    end
  end
end
```

A Simple Filter Example

```
terra runlaplace(input: rawstring,
output: rawstring) : {}
  var i = GreyscaleImage {}
  var o = GreyscaleImage {}
  i:load(input)
  laplace(&i,&o)
  o:save(output)
  i:free(); o:free()
end
```

Optimize The Filter

```
function blockedloop(N, blocksizes, bodyfn)
  local function generatelevel(n, ii, jj, bb)
    if n > #blocksizes then
      return bodyfn(ii, jj)
    end
    local blocksize = blocksizes[n]
    return quote
      for i = ii, min(ii+bb,N), blocksize do
        for j = jj, min(jj+bb,N), blocksize do
          [ generatelevel(n+1,i,j,blocksize) ]
        end
      end
    end
  end
  return generatelevel(1,0,0,N)
end
```

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GreyscaleImage = Image(float)
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out: &GreyscaleImage) : {}
  --shrink result, do not calculate boundaries
  var newN = img.N - 2
  out:init(newN)
  [blockedloop(newN,{128,64,1}, function(i,j)
    return quote
      var v = -img:get(i+0,j+1) - img:get(i+2,j+1)
      - img:get(i+1,j+2) - img:get(i+1,j+0)
      + 4 * img:get(i+1,j+1)
      out:set(i,j,v)
    end
  end)]
end
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- Terra expression: $\dot{e}$, specialization of Terra: $\xrightarrow{S}$

- Specialized Terra expression: $\underline{\dot{e}}$, execution of specailized Terra expression: $\xrightarrow{T}$

Terra Core

Lua Syntax:

$$e ::= b \mid \dot{T} \mid x \mid let\ x\ =\ e\ in\ e \mid x\ :=\ e \mid e(e) \mid fun(x)\{e\} \mid tdecl \mid$$
$$ter\ e(x:\ e):\ e\{\dot{e}\} \mid \backslash \dot{e}$$
$$v ::= b \mid l \mid \dot{T} \mid\ <\Gamma, x, e> \mid \underline{\dot{e}}$$
$$\dot{T} ::= \dot{B} \mid \dot{T} \rightarrow \dot{T}$$

Terra Core

Terra Syntax:

$$\dot{e} ::= b \mid x \mid \dot{e}(\dot{e}) \mid tlet\ x:\ e\ =\ \dot{e}\ in\ \dot{e} \mid [e]$$

$$\underline{e} ::= b \mid \underline{x} \mid \underline{e}(\underline{e}) \mid tlet\ \underline{x}:\ \dot{T}\ =\ \underline{e}\ in\ \underline{e} \mid l$$

Terra Core

$$v \Sigma \xrightarrow{L} v \Sigma \qquad \text{(LVAL)}$$

$$\frac{\Sigma = \Gamma, S, F}{x \Sigma \xrightarrow{L} S(\Gamma(x)) \Sigma} \qquad \text{(LVAR)}$$

$$\frac{e_1 \Sigma_1 \xrightarrow{L} v_1 \Sigma_2 \quad \Sigma_2 = \Gamma, S, F \quad e_2 \Sigma_2[x \leftarrow v_1] \xrightarrow{L} v_2 \Sigma_3}{let \ x = e_1 \ in \ e_2 \ \Sigma \xrightarrow{L} v_2(\Sigma_3 \leftarrow \Gamma)} \qquad \text{(LLET)}$$

$$\frac{e \Sigma \xrightarrow{L} v \Gamma, S, F \quad \Gamma(x) = a}{x := e \ \Sigma \xrightarrow{L} v \Gamma, S[a \leftarrow v], F} \qquad \text{(LASN)}$$

Terra Core

$$\frac{\Sigma = \Gamma, S, F}{fun(x)\{e\}\ \Sigma \xrightarrow{L} <\Gamma, x, e>\ \Sigma} \qquad \text{(LFUN)}$$

$$e_1\ \Sigma_1 \xrightarrow{L} <\Gamma_1, x, e_3> \quad e_2\ \Sigma_2 \xrightarrow{L} v_1\ \Gamma_2, S, F$$

$$\frac{a\ fresh \quad e_3\ \Gamma_1[x \leftarrow a], S[a \leftarrow v_1], F \xrightarrow{L} v_2\ \Sigma_3}{e_1(e_2)\ \Sigma_1 \xrightarrow{L} v_2\ (\Sigma_3 \leftarrow \Gamma_2)} \qquad \text{(LAPP)}$$

$$\frac{l\ fresh \quad \Sigma = \Gamma, S, F}{tdecl\Sigma \xrightarrow{L} l\ \Gamma, S, F[l \leftarrow \bullet]} \qquad \text{(LTDECL)}$$

Terra Core

$$e_1 \ \Sigma_1 \xrightarrow{L} l \ \Sigma_2 \quad e_2 \ \Sigma_2 \xrightarrow{L} \dot{T}_1 \ \Sigma_3 \quad e_3 \ \Sigma_3 \xrightarrow{L} \dot{T}_2 \ \Sigma_4$$
$$\Sigma_4 = \Gamma_1, S_1, F_1 \quad \underline{x} \text{ fresh}$$
$$\dot{e} \ \Sigma_4[x \leftarrow \underline{x}] \xrightarrow{S} \underline{\dot{e}} \ \Gamma_2, S_2, F_2 \quad F_2(l) = \bullet$$

$$\frac{}{\textit{ter } e_1(x : e_2) : e_3\{\dot{e}\} \ \Sigma_1 \xrightarrow{L} l \ \Gamma_1, S_1, F_2[l \leftarrow < \underline{x}, \dot{T}_1, \dot{T}_2, \underline{\dot{e}} >]} \quad \text{(LTDEFN)}$$

$$\frac{\dot{e} \ \Sigma_1 \xrightarrow{S} \underline{\dot{e}} \ \Sigma_2}{\iota\dot{e} \ \Sigma_1 \xrightarrow{L} \underline{\dot{e}} \ \Sigma_2} \quad \text{(LTQUOTE)}$$

Terra Core

$$e_1\ \Sigma_1 \xrightarrow{L} l\ \Sigma_2 \quad e_2\ \Sigma_2 \xrightarrow{L} b_1\ \Sigma_3$$

$$\Sigma_3 = \Gamma, S, F \quad F(l) = <\dot{\underline{x}}, \dot{T}_1, \dot{T}_2, \dot{\underline{e}}> \quad b_1 \in \dot{T}_1$$

$$\frac{[\dot{\underline{x}} : \dot{T}_1], [l : \dot{T}_1 \to \dot{T}_2], F_2 \vdash \dot{\underline{e}} : \dot{T}_2 \quad \dot{\underline{e}}[\dot{\underline{x}} \leftarrow b], F \xrightarrow{T} b_2}{e_1(e_2)\ \Sigma_1 \xrightarrow{L} b_2\ \Sigma_3} \quad \text{(LTAPP)}$$

Terra Core

$$b \, \Sigma \xrightarrow{S} b \, \Sigma \qquad \text{(SBAS)}$$

$$\frac{\dot{e}_1 \, \Sigma_1 \xrightarrow{S} \underline{\dot{e}_1} \, \Sigma_2 \quad \dot{e}_2 \Sigma_2 \xrightarrow{S} \underline{\dot{e}_2} \Sigma_3}{\dot{e}_1(\dot{e}_2) \, \Sigma_1 \xrightarrow{S} \underline{\dot{e}_1}(\underline{\dot{e}_2}) \, \Sigma_3} \qquad \text{(SAPP)}$$

$$e \, \Sigma_1 \xrightarrow{L} \dot{T} \Sigma_2 \quad \dot{e}_1 \, \Sigma_2 \xrightarrow{S} \underline{\dot{e}_1} \, \Sigma_3 \quad \underline{\dot{x}} \, \text{fresh}$$

$$\frac{\Sigma_3 = \Gamma, S, F \quad \dot{e}_2 \, \Sigma_3[x \leftarrow \underline{\dot{e}_2}] \xrightarrow{S} \underline{\dot{e}_2} \, \Sigma_4}{\text{tlet } x : e = \dot{e}_1 \, \text{in } \dot{e}_2 \, \Sigma_1 \xrightarrow{S} \text{tlet } \underline{\dot{x}} : \dot{T} = \underline{\dot{e}_1} \, \text{in } \underline{\dot{e}_2} \, (\Sigma_4 \leftarrow \Gamma)} \qquad \text{(SLET)}$$

Terra Core

$$\frac{e \; \Sigma_1 \xrightarrow{L} \underline{\dot{e}} \Sigma_2}{[e] \; \Sigma_1 \xrightarrow{S} \underline{\dot{e}} \; \Sigma_2} \qquad \text{(SESC)}$$

$$\frac{[x] \; \Sigma_1 \xrightarrow{S} \underline{\dot{e}} \; \Sigma_2}{x \; \Sigma_1 \xrightarrow{S} \underline{\dot{e}} \; \Sigma_2} \qquad \text{(SVAR)}$$

Terra Core

$$b \: \dot{\Gamma}, F \xrightarrow{T} b \tag{TBAS}$$

$$l \: \dot{\Gamma}, F \xrightarrow{T} l \tag{TFUN}$$

$$\underline{x} \: \dot{\Gamma}, F \xrightarrow{T} \dot{\Gamma}(\underline{x}) \tag{TVAR}$$

$$\frac{\underline{\dot{e}_1} \: \dot{\Gamma}, F \xrightarrow{T} v_1 \quad \underline{\dot{e}_2} \dot{\Gamma}[\underline{x} \leftarrow v_1], F \xrightarrow{T} v_2}{tlet \: \underline{x} : \dot{T} = \underline{\dot{e}_1} \: in \: \underline{\dot{e}_2} \: \dot{\Gamma}, F \xrightarrow{T} v_2} \tag{TLET}$$

$$\frac{\begin{array}{c} \underline{\dot{e}_1} \: \dot{\Gamma}, F \xrightarrow{T} l \quad \underline{\dot{e}_2} \: \dot{\Gamma}, F \xrightarrow{T} v_1 \\ F(l) = < \underline{x}, \dot{T}_1, \dot{T}_2, \underline{\dot{e}_3} > \quad \underline{\dot{e}_3} \: \dot{\Gamma}[\underline{x} \leftarrow v_1], F \xrightarrow{T} v_2 \end{array}}{\underline{\dot{e}_1}(\underline{\dot{e}_2}) \: \dot{\Gamma}, F \xrightarrow{T} v_2} \tag{TAPP}$$

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- Type Reflection API.

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- Or we need to re-compile y when x_1 changes.
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- Separate the declaration and definition.

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- So no need for type annotations.
- Easier to override the default behavior of a type.

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- Also the metamethods table: override certain compile-time behaviors(e.g. implicit conversion).

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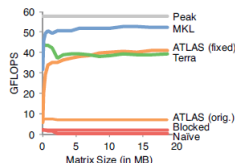
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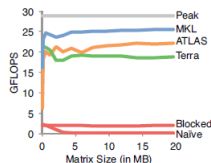
(a) DGEMM Performance   (b) SGEMM Performance

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Shortages

- Lua is not statically typed.

Reference

- Zachary DeVito, James Hegarty, Alex Aiken, Pat Hanrahan, and Jan Vitek. 2013. Terra: A multi-stage language for high-performance computing. In Proceedings of the 34th ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI'13). ACM, New York, 105–116. DOI:https://doi.org/10.1145/2491956.2462166
- Terra: A low-level counterpart to Lua. https://terralang.org/