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

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March 5, 2023

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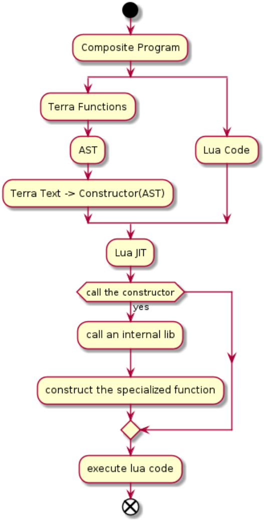
- Terra code runs independently, to avoid including high-level features.
- Lua's stack-based C API makes it easy to interface with legacy code.

Two-Language Design



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) : {}
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  out:init(newN)
  [blockedloop(newN,{128,64,1}, function(i,j)
    return quote
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      - 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:

$$
\begin{aligned}
e \; &::= b \mid \dot{T} \mid x \mid let\, x \;=\; e\; in\; e \mid x \;:=\; e \mid e(e) \mid fun(x)\{e\} \mid tdecl \mid \\
&\qquad ter\, e(x:\; e):\; e\{\dot{e}\} \mid \backprime\dot{e} \\
v \; &::= b \mid l \mid \dot{T} \mid \; <\Gamma, x, e> \; \mid \underline{\dot{e}} \\
\dot{T} &::= \dot{B} \mid \dot{T} \rightarrow \dot{T}
\end{aligned}
$$

Terra Core

Terra Syntax:

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

Terra Core

$$v\,\Sigma \xrightarrow{L} v\,\Sigma \tag{LVAL}$$

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

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

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

Terra Core

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

$$\frac{e_1\ \Sigma_1 \xrightarrow{L} <\Gamma_1, x, e_3> \quad e_2\ \Sigma_2 \xrightarrow{L} v_1\ \Gamma_2, S, F \qquad a\ fresh \quad e_3\ \Gamma_1[x \leftarrow a], S[a \leftarrow v_1], F \xrightarrow{L} v_2\ \Sigma_3}{e_1(e_2)\ \Sigma_1 \xrightarrow{L} v_2\ (\Sigma_3 \leftarrow \Gamma_2)} \quad \text{(LAPP)}$$

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

Terra Core

$$
\frac{
\begin{array}{c}
e_1\ \Sigma_1 \xrightarrow{L} l\ \Sigma_2 \quad e_2\ \Sigma_2 \xrightarrow{L} \dot{T}_1\ \Sigma_3 \quad e_3\ \Sigma_3 \xrightarrow{L} \dot{T}_2\ \Sigma_4 \\
\Sigma_4 = \Gamma_1, S_1, F_1 \quad \underline{\dot{x}}\ \mathit{fresh} \\
\dot{e}\ \Sigma_4[x \leftarrow \underline{\dot{x}}] \xrightarrow{S} \underline{\dot{e}}\ \Gamma_2, S_2, F_2 \quad F_2(l) = \bullet
\end{array}
}{
\mathit{ter}\ e_1(x : e_2) : e_3\{\dot{e}\}\ \Sigma_1 \xrightarrow{L} l\ \Gamma_1, S_2, F_2[l \leftarrow < \underline{\dot{x}}, \dot{T}_1, \dot{T}_2, \underline{\dot{e}} >]
} \quad \text{(LTDEFN)}
$$

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

Terra Core

$$\frac{\begin{array}{c} e_1\ \Sigma_1 \xrightarrow{L} l\ \Sigma_2 \quad e_2\ \Sigma_2 \xrightarrow{L} b_1\ \Sigma_3 \\ \Sigma_3 = \Gamma, S, F \quad F(l) =< \underline{\dot{x}}, \dot{T}_1, \dot{T}_2, \underline{\dot{e}} > \quad b_1 \in \dot{T}_1 \\ [\underline{\dot{x}} : \dot{T}_1], [l : \dot{T}_1 \rightarrow \dot{T}_2], F_2 \vdash \underline{\dot{e}} : \dot{T}_2 \quad \underline{\dot{e}}[\underline{\dot{x}} \leftarrow b], F \xrightarrow{T} b_2 \end{array}}{e_1(e_2)\ \Sigma_1 \xrightarrow{L} b_2\ \Sigma_3} \quad \text{(LTAPP)}$$

Terra Core

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

$$\frac{\dot{e_1}\ \Sigma_1 \xrightarrow{S} \underline{\dot{e_1}}\ \Sigma_2 \quad \dot{e_2}\Sigma_2 \xrightarrow{S} \underline{\dot{e_2}}\Sigma_3}{\dot{e_1}(\dot{e_2})\ \Sigma_1 \xrightarrow{S} \underline{\dot{e_1}}(\underline{\dot{e_2}})\ \Sigma_3} \qquad \text{(SAPP)}$$

$$\frac{e\,\Sigma_1 \xrightarrow{L} \dot{T}\,\Sigma_2 \quad \dot{e_1}\ \Sigma_2 \xrightarrow{S} \underline{\dot{e_1}}\ \Sigma_3 \quad \underline{\dot{x}}\ \mathit{fresh} \\ \Sigma_3 = \Gamma, S, F \quad \dot{e_2}\ \Sigma_3[x \leftarrow \underline{\dot{e_2}}] \xrightarrow{S} \underline{\dot{e_2}}\ \Sigma_4}{\mathit{tlet}\ x : e = \dot{e_1}\ \mathit{in}\ \dot{e_2}\ \Sigma_1 \xrightarrow{S} \mathit{tlet}\ \underline{\dot{x}} : \dot{T} = \underline{\dot{e_1}}\ \mathit{in}\ \underline{\dot{e_2}}\ (\Sigma_4 \leftarrow \Gamma)} \qquad \text{(SLET)}$$

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

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

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

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

$$\frac{\underline{\dot{e_1}}\ \dot{\Gamma}, F \xrightarrow{T} v_1 \quad \underline{\dot{e_2}}\dot{\Gamma}[\underline{\dot{x}} \leftarrow v_1], F \xrightarrow{T} v_2}{tlet\ \underline{\dot{x}} :\ \dot{T} = \underline{\dot{e_1}}\ in\ \underline{\dot{e_2}}\ \dot{\Gamma}, F \xrightarrow{T} v_2} \tag{TLET}$$

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- Type Reflection API.

Why Specialize Eagerly?

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- Separate the declaration and definition.

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- Easier to override the default bevavior of a type.

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

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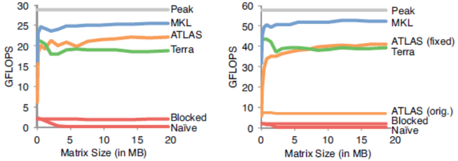

(a) DGEMM Performance (b) SGEMM Performance

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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/`