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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- Compiler: generate taget code based on the plan.
- Runtime: support the generated code and provide feedback to the optimizer.
- Problem1: How can we get the runtime statistics in the compiler and generate high-performance code dynamically?
- Problem2: How can we re-use legacy libraries?

Two-Language Design

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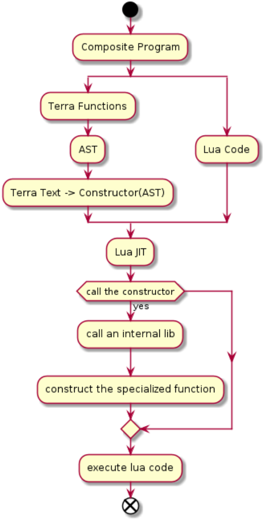
- Terra code runs independently, to avoid including high-level features.
- Lua's stack-based C API makes it easy to interface with legacy code.

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.

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- Lua expression: e, evaluation of Lua: $\xrightarrow{L}$
- 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:

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

Terra Core

Terra Syntax:

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

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

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

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

Terra Core

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

Terra Core

$$b\,\Sigma \xrightarrow{S} b\,\Sigma \tag{SBAS}$$

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

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

Terra Core

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

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

Terra Core

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

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

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

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

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- No proof! :)

Some Important Designs

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- Perform typechecking and linking lazily.
- Type Reflection API.

Why Specialize Eagerly?

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\begin{aligned}
&let\,x_1 \;=\; 0 \\
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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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- Shorter code, easier to read/write/maintain.

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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 highperformance 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/