In-Place Array Update in a Dataflow Synchronous Language

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Synchronous Block Diagrams - SCADE

- DSL for modeling/implementing real-time control software
- Wires define streams of values
- All nodes progress at the same speed

1http://www.esterel-technologies.com/
node foo(a: int) = (c: int) {
    c = b + 1 (* c_t = b_t + 1 *)
    b = a + (0 -> pre b) (* b_0 = a_0 *)
    (* b_t = a_t + b_{t-1} *)
}

\[
\begin{array}{c}
\textbf{a} \\
\oplus
\end{array}
\quad
\begin{array}{c}
b \\
\oplus
\end{array}
\quad
\begin{array}{c}
c
\end{array}
\begin{array}{c}
0
\end{array}
\quad
\begin{array}{c}
\rightarrow
\end{array}
\quad
\begin{array}{c}
\textbf{pre}
\end{array}
\quad
\begin{array}{c}
1
\end{array}
\]
Equation Ordering

```c
node foo(a: int) = (c: int) {
    c = b + 1  // (* c_t = b_t + 1 *)
    b = a + (0 -> pre b)  // (* b_0 = a_0 *)
    // (* b_t = a_t + b_{t-1} *)
}
```

Implicit ordering of equations given by data dependencies
- Ordering in source code doesn’t matter

Allow feedback loops
- Every dependency loop must cross a delay
Compilation to efficient C code

```c
node foo(a: int) = (c: int) {
    c = b + 1 /* c_t = b_t + 1 */

    b = a + (0 -> pre b) /* b_0 = a_0 */
    /* b_t = a_t + b_{t-1} */
}
```

Generated C code

```c
// Computes a time step of foo
void foo_step(foo_state_t* state, int a, int* c) {
    int b = a + ((t == 0) ? 0 : state->b);
    *c = b + 1;

    state->b = b; // Update state
}
```
Functional Arrays

- Declare a new array and read from it
  
  ```
  e  =  d^1000
  f  =  e[4]
  ```

- Define a new array from an old one
  
  ```
  g  =  e[3] <- 42
  ```
Functional Arrays

- Declare a new array and read from it
  \[
  e = d^{1000} \\
  f = e[4]
  \]

- Define a new array from an old one
  \[
  g = e[3] <- 42
  \]

Immutable arrays: no in-place update

```c
// Generated C code
int e[1000] = { d };
int f = e[4];

int g[1000];
memcpy(g, e, 1000*sizeof(int));
g[3] = 42;
```

Costly operation
Problem

How to avoid array copies ... 

... while keeping functional semantics?
Destructive Updates

Ensure no array is accessed after being updated

- Ensure arrays are updated only once
- Add dependencies from reads to writes
- Let the scheduling algorithm do the job

(* Consume a, reuse its memory for b *)
\[
b = a[0] \leftarrow 0
\]

(* Access a *)
\[
c = a[0]
\]

C must be executed before b

Copies are no longer needed

- Modifications of the original array cannot be observed
- Reuse the memory of the original array
Strengths of the Destructive Update Approach

Keeps pure functional semantics

Removes all implicit copies

- Reject programs that cannot be implemented without copies
- Explicit copies with the `copy` operator if needed
- No hidden performance cost

Direct mapping from source to generated code

- Only dependency analysis is more complex
- Required by certification authorities
Inter-Reaction Copies

What about pre? Two solutions:

1. Insert a copy at every pre
2. Handle inter-reaction aliasing

\[(\ast \ b_t \ \text{consumes } a_t \ \ast)\]
\[b = a[0] \leftarrow 0\]

\[(\ast \ c_{t+1} \ \text{accesses } a_t \ \ast)\]
\[c = (\text{pre } a)[0]\]

\[c_{t+1} \text{ must be executed before } b_t\]

Must retim\text{e} equations

- Compute \(c_t\) at time \(t - 1\)
Problems to Solve

Inter-Reaction Alias Analysis
- Avoid unnecessary explicit copies

Array Memory Management
- Arrays outlive a single time step

Modular Compilation
- Compile a node independently of its calling context
- Unknown aliasing between arguments
- Retiming imposed by feedback loops
- The alternative is inlining: exponential code size
node f(A, B: int[8])
    = (c: int) {
        D = B[0] <- 0
    }

(* Without aliasing *)
x = f(A', B')

(* With aliasing *)
y = f(A', A')

Is there a dependency from Read A to Write B?
Module Compilation - Unknown Aliasing

```javascript
node f(A, B: int[8])
    = (c: int) {
        D = B[0] <- 0
    }

(* Without aliasing *)
x = f(A', B')

(* With aliasing *)
y = f(A', A')
```

Expose reads and writes to the calling context
Modular Compilation - Unknown Aliasing

\[
\text{node } f(A, B: \text{int}[8]) = (c: \text{int}) \{
D = B[0] \leftarrow 0 \\
\}
\]

(* Without aliasing *)
x = f(A', B')

(* With aliasing *)
y = f(A', A')

The context adds feedback loops if needed
Dependency Graph

Dependencies are of the form:

$$\forall t \in \mathbb{N} : a_t \text{ depends on } b_{t-w} \quad \text{with } w \in \mathbb{Z} \text{ constant.}$$

Dependencies represented by a weighted graph:

```plaintext
node foo(a, b: int) = (c: int) {
  (* c_t = a_t + b_{t-1} *)
  c = 0 -> a + pre b
}
```
How can we schedule this node?
{a_{t-1}, b_t} \text{ before } \{d_t, e_t\}
Modular Compilation - Feedback Loops

\[ \{d_t, e_t\} \text{ before } \{a_{t-1}, b_t\} \]
Modular Compilation - Feedback Loops

- $a_{t-1}$ and $b_t$ can be executed atomically
- $c_t$ can be executed atomically
- $d_t$ and $e_t$ can be executed atomically
Grayboxing

Grayboxing: Partitioning into atomic subnodes

- Subnodes are compiled independently
- The calling context orders subnodes
- Avoid a full inlining
Grayboxing Definition

A grayboxing is given by:

- A partitioning $X^0, \ldots, X^{k-1}$ of equations in atomic sub-nodes
- A retiming function for each sub-node $r_i : X_i \rightarrow \mathbb{Z}$
  - $a_t$ is computed at the reaction $t + r(a)$
- A dependency relation $X \xrightarrow{w} Y$ on sub-nodes
  - $X \xrightarrow{w} Y \implies Y_t$ depends on $X_{t-w}$

A Grayboxing must:

- Respect dependencies between equations
- Not reject any calling context

Extension of [Pouzet and Raymond 2009] for retiming
Finding a Minimal Grayboxing

**Goal:** Minimize the Number of Partitions

Optimal Solution: NP-Complete
- Encode the problem for an SMT solver

Heuristic: Find a Good-Enough Partitioning
- Optimal on inputs and outputs
- Based on an existing heuristic that doesn’t handle retiming

See the paper for more information
Conclusion

In-place updates in a synchronous dataflow language

- Avoid copy operations
- Keeps pure functional semantics
- No hidden performance cost
- No expressivity loss

Relies on scheduling constraints

- Ensure no array is accessed after being written to
- Leverages the existing scheduling algorithms
Destructive Updates for Synchronous Dataflow Languages

With copying \texttt{pre}

- Minimal alteration of the compilation process
- Arrays copied at the end of iterations

With inter-iteration aliasing

- \texttt{pre} creates aliasing instead of copying
- Need for retiming created by iter-iteration aliasing
- Context-aware scheduling and retiming for more genericity
- Modular compilation enabled by the grayboxing technique