Spot: A Programming Language for Verified Flight Software

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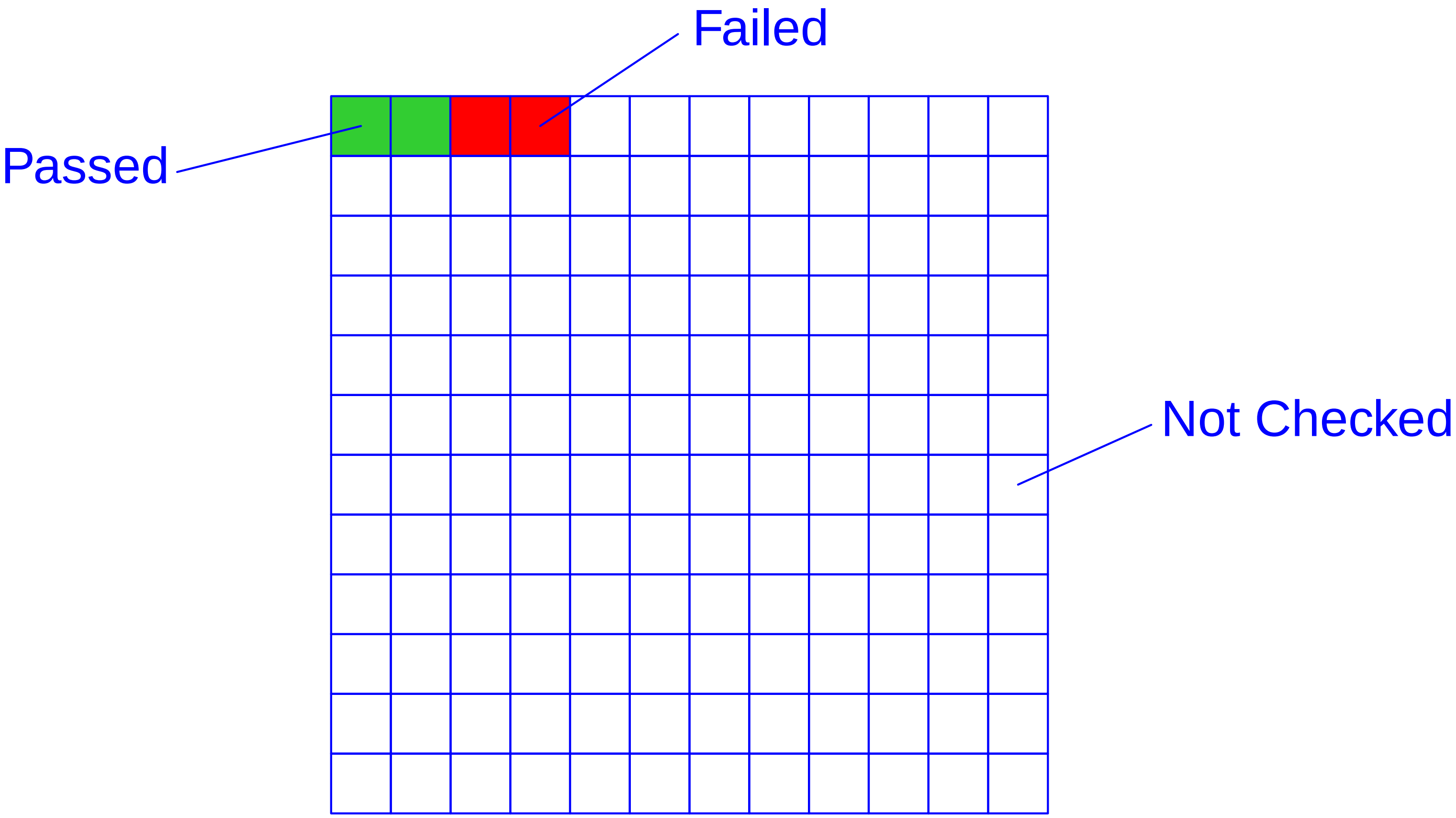
Motivation

- Most flight software (FSW) today is written in C
- Pros
  - ✓ Familiar
  - ✓ Simple
  - ✓ Low overhead
  - ✓ Easy to reason about resource use (speed, memory, power)
- Cons
  - X Lacks important abstractions for FSW
  - X **Requires** unsafe, low-level code
  - X Verification and validation (V&V) is very expensive

Example



Failed

Passed

Not Checked

Mars Science Laboratory (MSL) FSW coverage using the Spin model checker

Other Options

1. Use C++
   - ✓ Classes and templates support abstractions
   - ✓ Performs well
   - X Complex, opaque
   - X Still low-level, hard to verify
   - X Requires wholesale rewriting of existing FSW
2. Use a modern high-level language (Scala, Python, ...)
   - ✓ Abstraction support
   - ✓ Extensible syntax
   - X May not be feasible for embedded, low power
   - X Still hard to verify, requires rewriting

Our Solution: Spot

- New domain-specific language (DSL) for FSW
- Based on C
  - Retains the benefits of C for FSW programming
  - Interoperates with existing C code
- Key features
  - FSW abstractions: **modules** and **messages**
  - Improved memory management and precise accounting of **state**
  - Annotations for automatic testing and verification
  - Improved arrays, no pointer arithmetic
  - **Value type system** supporting auto-parallelization

Outline

- **The Spot language**
- Expected benefits of Spot
- Implementation status
- Future plans

Modules and Messages

Module Code

```
module Counter {
  priority P qsize 100;
  constructor create() {}
  state int count = 0;
  message void increment() priority P {
    next count = count + 1;
  }
  message int read() priority P {
    return count;
  }
}
```

Client Code

```
var Counter c = Counter.create();
var int count;
send c.increment();
send c.read() receive count;
printf("count is %d\n", count);
```

Messages

Counter

Client

Modules and Messages

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modules have state

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modules have state

messages operate on state

Messages

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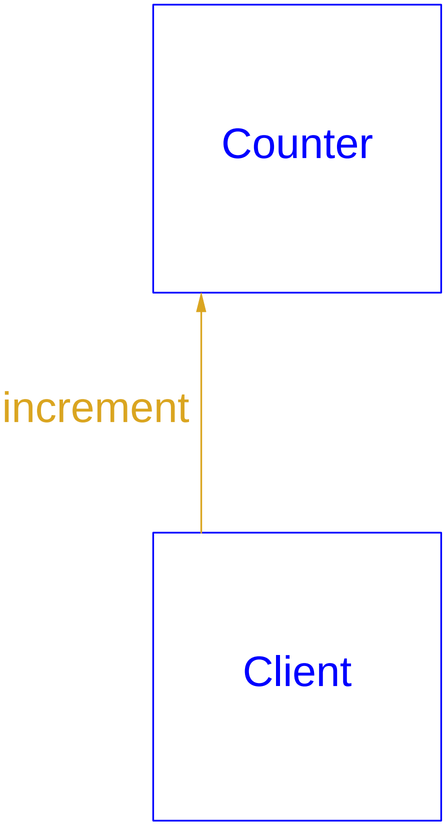

Counter

increment

Client

Modules and Messages

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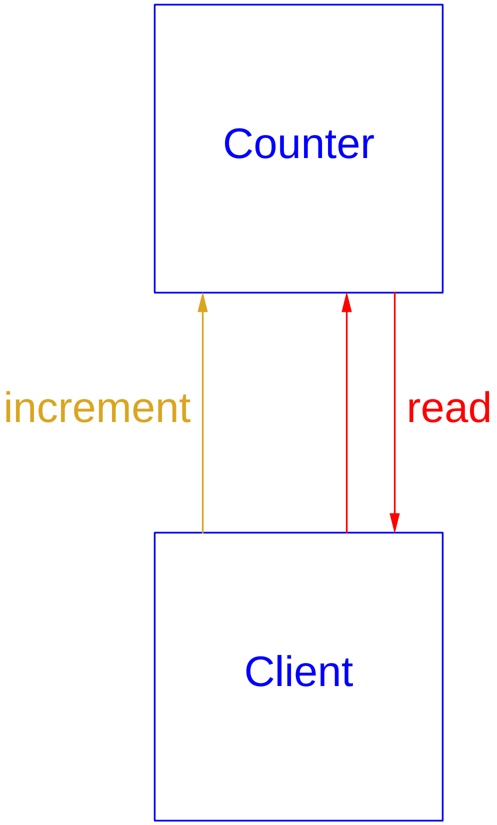

Counter

increment

read

Client

Memory Management

1. Stack variables: As in C
2. Message-local heap variables
    - Are created during a message invocation
    - Do not persist across messages
    - Are automatically reclaimed at the end of a message
3. State variables
    - Must be declared
        - With `state` keyword
        - Inside a module definition
    - Are associated with a module instance *m*
    - Persist across all messages received by *m*

There are no global variables in Spot

Typing Guarantees

- Spot enforces two memory partitioning guarantees:
  1. No two module instances share any memory
  2. No state points to non-state, and vice versa
- Enforcement uses a combination of
  - Type consistency checks
  - Implicit deep copies of objects

```
module M {
  state T x;
  ...
  function void f(T *state y) { ... }
  message void m(T* y) priority P {
    f(&x);
    f(y);
  }
}
```

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    f(&x); // state->state: normal pass-by-pointer
    f(y); // non-state->state: implicit deep copy
  }
}
```

Updating State

- State update
  - Is called out with the **`next`** keyword
  - Occurs all at once at the end of message processing
- Motivation
  - Buffer current state for possible undo
  - Separate current state from next state in assertions

```
module Counter {
  state count = 0;
  ...
  message int read_and_increment() priority P {
    next count = count + 1;
    return count;
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count is *n*

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}
```

count is n

set count to $n + 1$ and return n

Annotation Language

- Spot has a simple but powerful annotation language built in
- Syntax: @ *identifier* (*expression*)
- Semantics: defined by pluggable checker
  - Spin code generation
  - Design-by-contract-style runtime checks

```
module Counter {
  state count = 0;
  ...
  message void increment() priority P
    private @assumes(count >= 0)
    private @guarantees(next count == count + 1)
  {
    next count = count + 1;
  }
}
```

Other Features of Spot

- Improved arrays
  - Arrays store their length and are bounds-checkable
  - Fortran-style loops and array slices
  - Multidimensional arrays with variable dimension sizes
  - No pointer indexing! (Arrays ≠ pointers in Spot)
- Value types
  - You can define and create immutable struct values

```
declare value type tree_t;
type tree_t = value struct { tree_t* left; tree_t* right; }
```

  - Essential for auto-parallelization
  - C **requires** pointers to mutable structs

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Expected Benefits of Spot

- Improved programmability vs. C
  - Module and message abstractions
  - Memory management and state partitioning
  - Improved arrays and value types
- Atomic update of state
- Auto-generation of
  - Verification code (Spin, runtime checks)
  - Telemetry code
- Multicore support
- C compatibility

Atomic Update

- Message handlers update state atomically
  - Modules $M_1, \ldots, M_n$ run concurrently
  - Within a module M_i, handlers run sequentially
- Message m can be safely aborted, restarted in many cases:
  - If it sends no message m'
    - All state accessed by m is known and buffered
    - Just throw away next state and start over
  - If it sends a message m' with return type `void`
    - Defer sending of m' until m's computation is done
- Big step towards controlled software reset
  - Avoid sledgehammer of system reboot

Verification Code

- Easy to translate annotations into runtime checks
  - Test cases, e.g., input ranges
  - `@assumes`, `@guarantees`, `@assert`
- Spin code generation is also straightforward
  - C program is the Promela model
  - Spot semantics reduces the state space
- Should vastly reduce the cost of V&V for FSW

Telemetry Code

- Telemetry causes lots of code generation
  - A pain to manage using current techniques
  - Redundant with information already in FSW code
- Spot can do much of this automatically
  - Engineering, Housekeeping, and Accountability
    - Is state
    - Spot knows about it
  - Event Reporting (EVRs)
    - Are events associated with state change
    - Spot can check for specified state change and downlink as EVR

Multicore Support

- Each module is logically a thread, can go on its own core
- Message bodies can be parallelized
  - Use value types to minimize access to shared mutable data
    - Write helpers as pure functions
    - Enables auto-parallelization
  - Where mutable data is required (e.g., arrays)
    - Encapsulate parallel data structures behind library APIs
    - Update state at top-level only
- Concurrent message handling is future work

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Implementaton Status

- Language specification
  - Formal syntax
  - Informal semantics
- Compiler implementation
  - Alpha version (write in mix of Spot, C, and Scheme): done
    - Generates C and Promela (Spin) code
    - Links against runtime
  - Beta version: in progress
    - Parser is done
    - Spot-to-C and Spot-to-Promela code generators in progress
- Case studies
  - Compiled and ran simple examples
  - Working on more extensive examples drawn from MSL code

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Future Plans

- Further evaluation to answer research questions
  - What are the gains vs. plain C
    - In safety and verification?
    - In productivity?
  - What is the performance cost?
- Evaluate for deployment
  - Expect beta version of compiler by end of FY14
  - Several flight projects have expressed interest

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- Rafi Some
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  - Bill Whitaker
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  - Object-oriented and actor-based programming
  - State encapsulation
  - Functional programming