Real-Time Runtime Monitoring

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joint work with

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Need

How do you know your embedded software won’t fail?

- Certification (e.g., DO-178B) is largely process-oriented
- Testing exercises a small fraction of the state-space
- It's probably not formally verified
  - Even if so, just a small subsystem
  - And making simplifying assumptions

I'll argue: need to detect/respond at runtime

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Yes, it's *Still* a Problem

2005-2008:

- Malaysia Airlines Flight 124 (Boeing 777)
  - “Software anomaly”
- Qantas Airlines Flight 72 (Airbus A330)
  - Transient fault in the inertial reference units
- Space Shuttle STS-124 aborted launch
  - Bad assumptions about distributed fault-tolerance

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Just the FaCTS, Ma’am: The Constraints

Runtime monitoring for real-time embedded systems should satisfy the FaCTS:

- **F**unctionality: don’t change the target’s behavior
- **C**ertifiability: don't require re-certification, or make it easy
  Don't go changing sources.
- **T**iming: don’t interfere with the target’s timing
- **S**WaP: don’t exhaust size, weight, power reserves

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Outline

1. The *Copilot* language and compiler
2. Embedded domain-specific languages
3. Low-cost high-assurance
4. Pilot-study[1]: injecting software faults in a fault-tolerant air-speed system
5. Conclusions

[1]Pun intended

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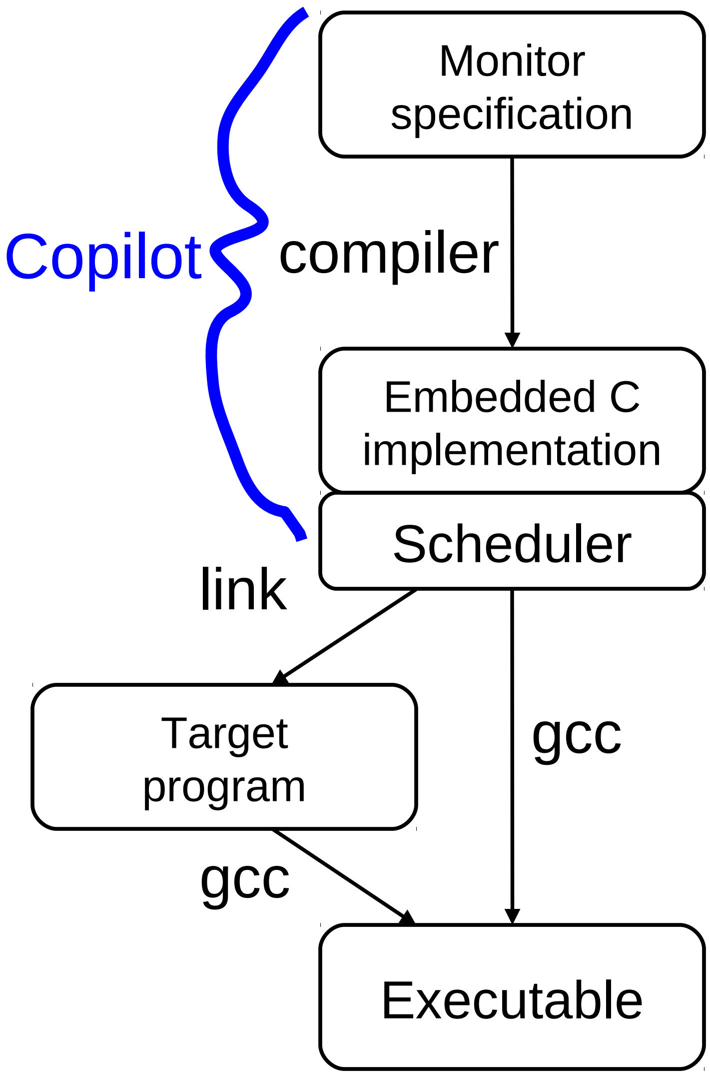
Copilot: Embedded System Monitoring

- *Copilot* is a language, compiler, and verification tools
- Compiles monitor specifications to embedded C
  - Constant time, constant space
  - Generates its own scheduler: no OS needed
  - Don't inline the monitors
- Monitor program:
  - **Inputs**: monitored memory
  - **Outputs**: trigger functions, if a monitor is violated



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Copilot Language

A simple stream language

- Think: data-flow of infinite lists (streams) – LUSTRE
- Streams give a discrete, synchronous view of real-time
- Strongly & statically typed variables with no lossy casts

```
let x = varW64 in
x .= [0] ++ x + 2
------------------
X → 0, 2, 4, 6 ...
```

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Copilot Interpreter (In One Slide)

```
interpret copilotVs extVs s =
  case s of
    Const c -> repeat c
    Var v -> getElem v copilotVs
    ExtVar _ v -> checkV v (\v' -> (getElem v' extVs))
    ExtArr _ (v,s') -> checkV v (\v' -> map (\i ->  getElem v' extVs
                                                  !! fromIntegral i)
                                             (interpret copilotVs extVs s'))
    Append ls s' -> ls ++ interpret copilotVs extVs s'
    Drop i s' -> drop i $ interpret copilotVs extVs s'
    F f _ s' -> map f (interpret copilotVs extVs s')
    F2 f _ s0 s1 -> zipWith f (interpret copilotVs extVs s0)
                              (interpret copilotVs extVs s1)
    F3 f _ s0 s1 s2 -> zipWith3 f
                       (interpret copilotVs extVs s0)
                       (interpret copilotVs extVs s1)
                       (interpret copilotVs extVs s2)
```

Parameterized on basic operators

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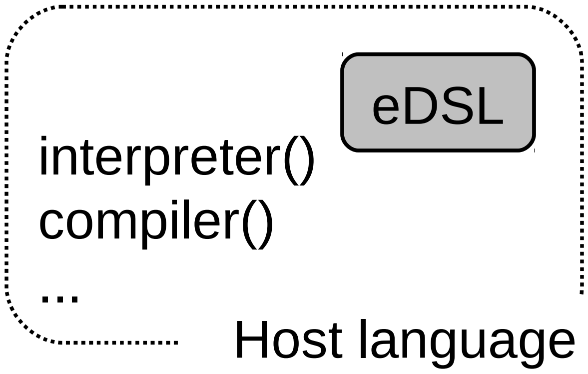
Point #1: Embedded DSLs Make Things Better

- A **domain-specific language (DSL)** is a special-purpose programming language.
  - E.g., sed/awk, Simulink, R
- An **embedded DSL (eDSL)** is a DSL written as a library in a general-purpose programming language
  - Often the host language is a functional language, e.g., Haskell, Scheme, OCaml



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Point #1: Embedded DSLs Make Things Better

Why eDSLs?

- Lexer, parser, type-checker, etc. for free and more likely correct
- Macro language for free (the entire host language)

  In eDSLs, the macro language is primary
- Libraries for free
- Much easier to make your own modifications

For Copilot: can we have the advantages of functional languages without its limitations (timing, control-flow, memory size)?

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Point #1: Embedded DSLs Make Things Better

Why not?

- The DSL syntax must be a “sub-syntax” of your host language
- In some cases, efficiency can be tricky
- More esoteric error messages
- eDSLs in certification unexplored
- Harder to make proprietary/closed source

Research topics!

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eDSLs: C'mon, Everybody's Doing It

- Eaton (embedded control systems)
- Ericsson (DSP)
- Credit Suisse and other trading houses (e.g., derivatives pricing)
- Galois (Numerous)

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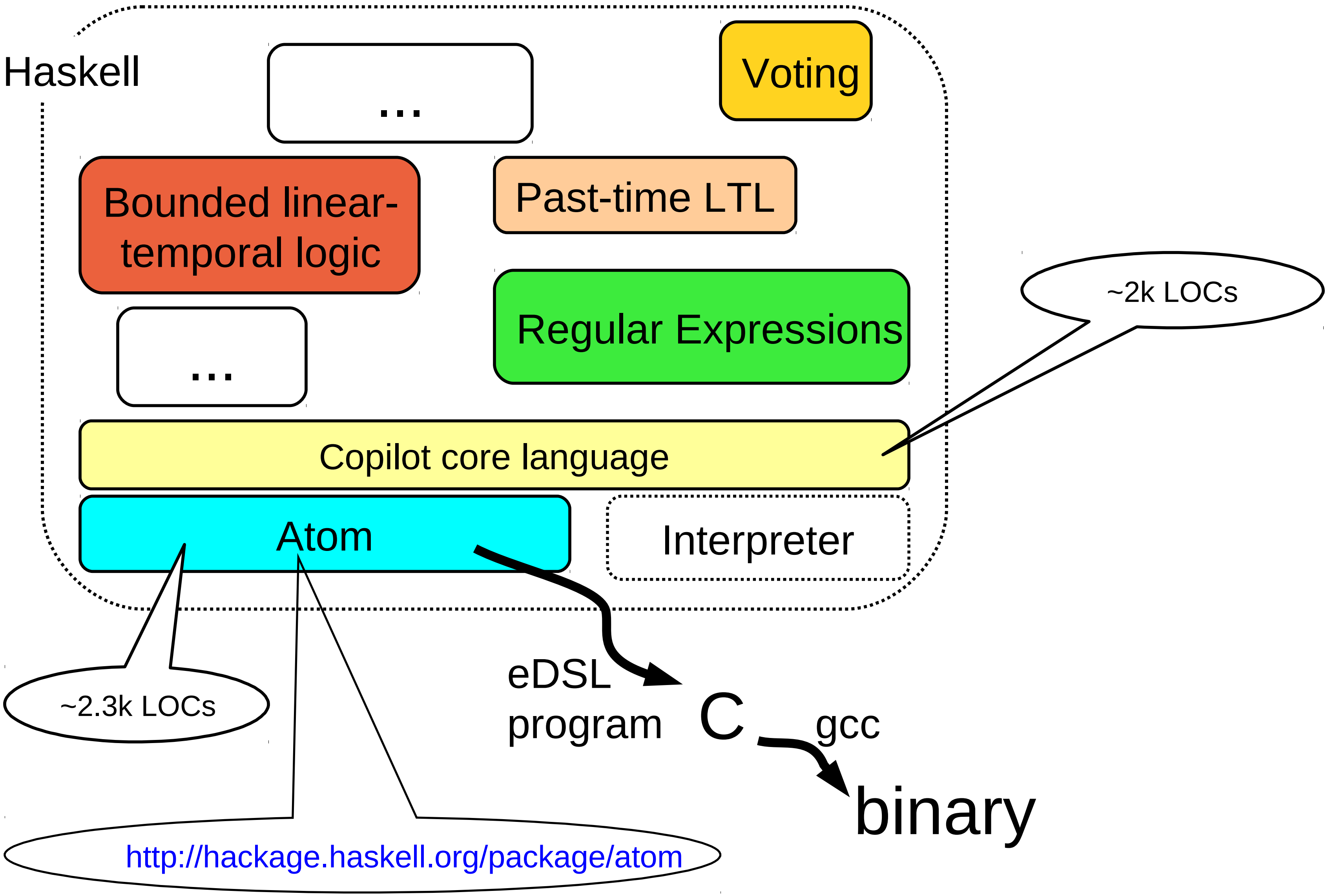
Copilot as an eDSL



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The Power of eDSLs

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```
-- external variables
t0     = extW8 "temp_probe_0"
t1     = extW8 "temp_probe_1"
t2     = extW8 "temp_probe_2"
cooler = extB  "fan_status"
-- Copilot variables
maj      = varW8 "maj"
check    = varB  "maj_check"
overHeat = varB  "over_heat"
monitor  = varB  "monitor"
--------------------------------------
engineMonitor = do
  let temps = map (< 250) [t0, t1, t2]
  maj      .= majority temps
  check    .= aMajority temps maj
  overHeat `ptltl`
    ((cooler || maj && check)
       `since' not maj)
  monitor .= not overHeat
  trigger monitor "shutoff" void
```

"If the majority of the three engine temperature probes has exceeded 250 degrees, then the cooler is engaged and remains engaged until the temperature of the majority of the probes drop to 250 degrees or less. Otherwise, trigger an immediate shutdown of the engine."

Libraries

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The Power of eDSLs

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Some problems for conventional compilers go away

- Don't have to add new language features (often)
- Don't need scripting languages

E.g., compiling distributed monitors is just another function:

```
compile program node
  (setCode (Just header)) baseOpts
```

```
distCompile program node headers =
  compile (program node) node
    (setCode (Just (headers node))) baseOpts
```

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Point #2: Low-Cost High-Assurance

Who watches the watchmen?

Some lessons:

- Types are free proofs
- (Try) to avoid compiler bugs/non-standard behavior
- Compile -Wall, compile -Wall, compile -Wall
- Ensure interpreter == compiler
- Ensure interpreter == compiler, millions of times
- Test coverage (line, branch, functional call) using *gcov*

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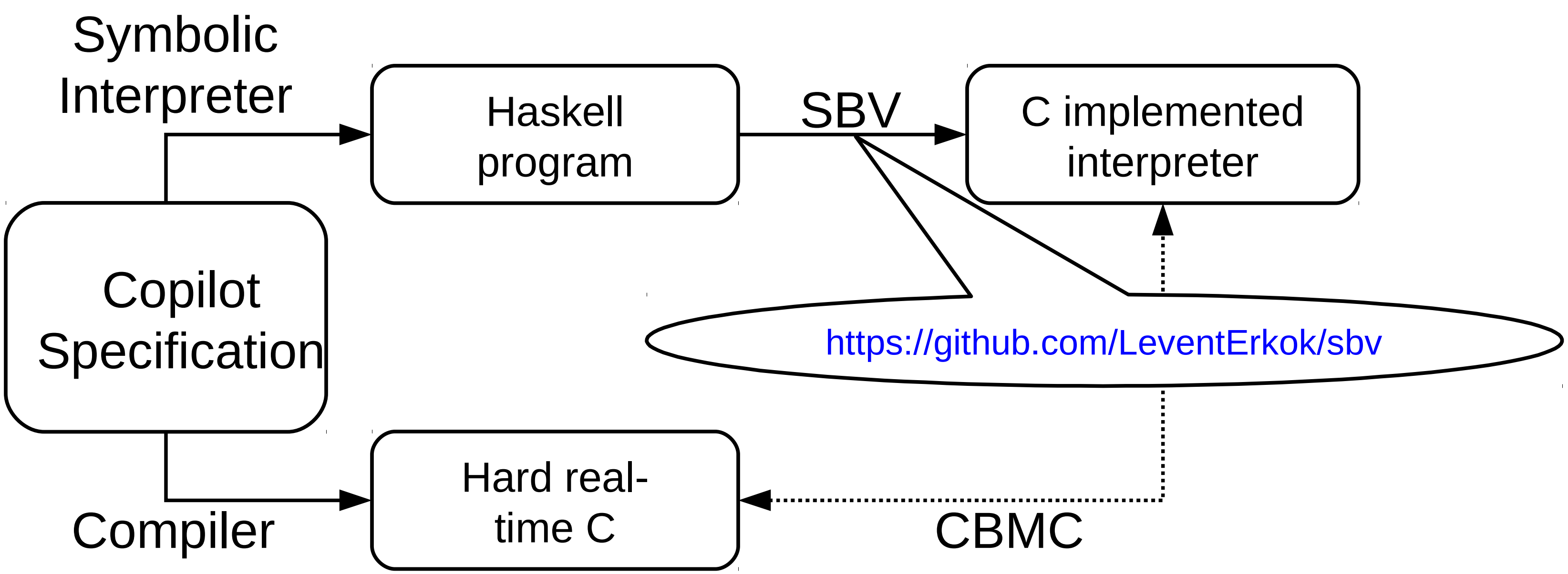
Point #2: Low-Cost High-Assurance

- Prove memory-safety.

  CBMC http://www.cprover.org/cbmc/

- Verify the compilation – a “poor man's verifying compiler) (future work)



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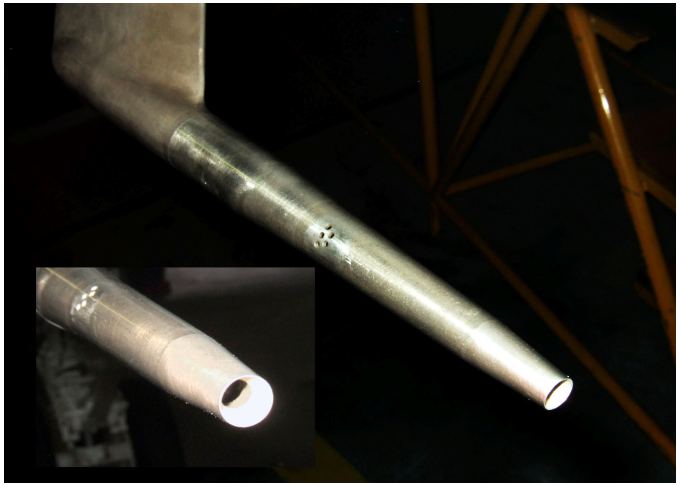
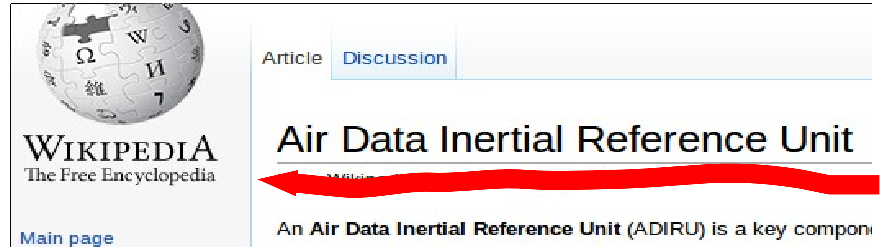
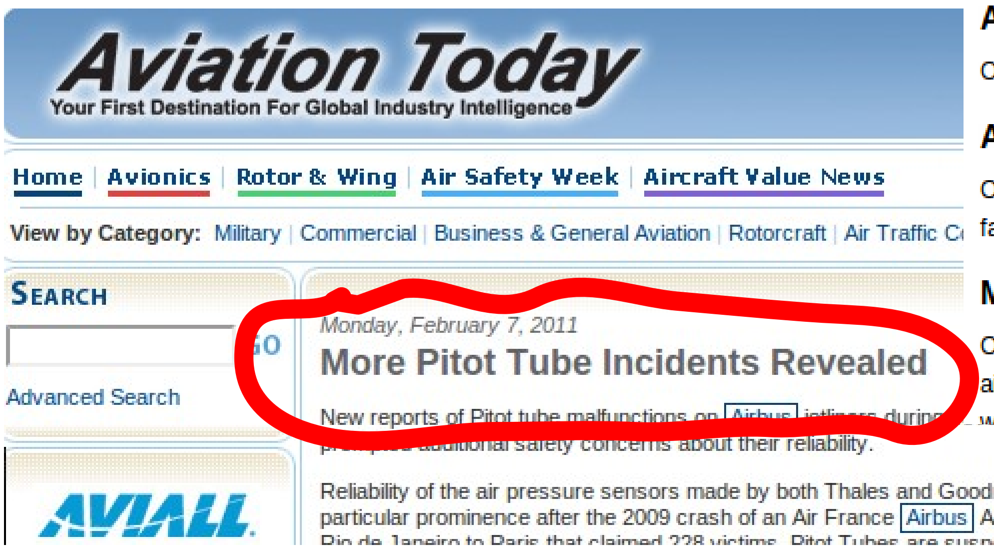
Interlude: Pitot Failures







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Interlude: Pitot Failures

Failures cited in

- Northwest Orient Airlines Flight 6231 (1974)---3 killed

  Increased climb/speed until uncontrollable stall

- Birgenair Flight 301, Boeing 757 (1996)---189 killed

  One of three pitot tubes blocked; faulty air speed indicator

- Aeroperú Flight 603, Boeing 757 (1996)---70 killed

  Tape left on the static port(!) gave erratic data

- Líneas Aèreas Flight 2553, Douglas DC-9 (1997)---74 killed
  - Freezing caused spurious low reading, compounded with a failed alarm system
  - Speed increased beyond the plane's capabilities
- Air France Flight 447, Airbus A330 (2009)---228 killed
  - Airspeed "unclear" to pilots
  - Still under investigation
- ...

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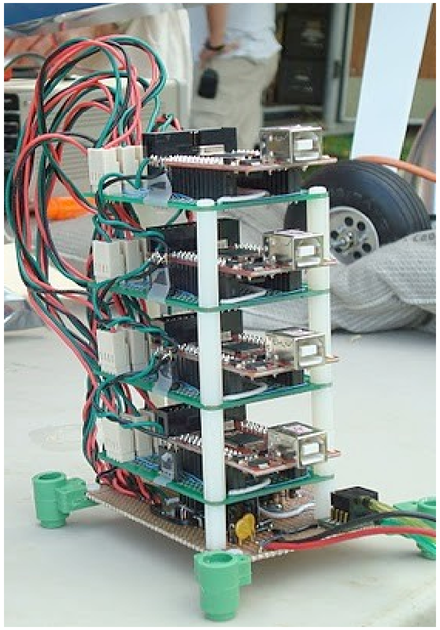
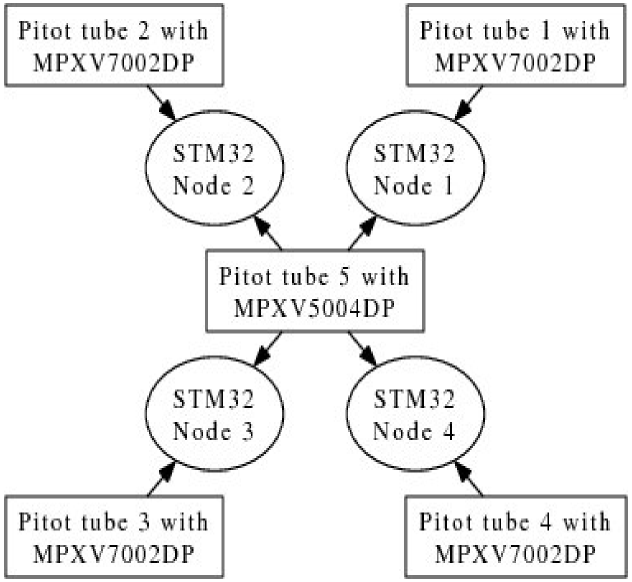
Test Bed

- Representative of fault-tolerant systems
- 4 X STM32 microcontrollers
- ARM Cortex M3 cores clocked at 72 Mhz
- 5 MPXV5004DP differential pressure sensors
  - Senses dynamic and static pitot tube pressure
  - Pitot tubes measure airspeed
- Designed to fit UAS (unpiloted air system)

  Size, power, weight,...





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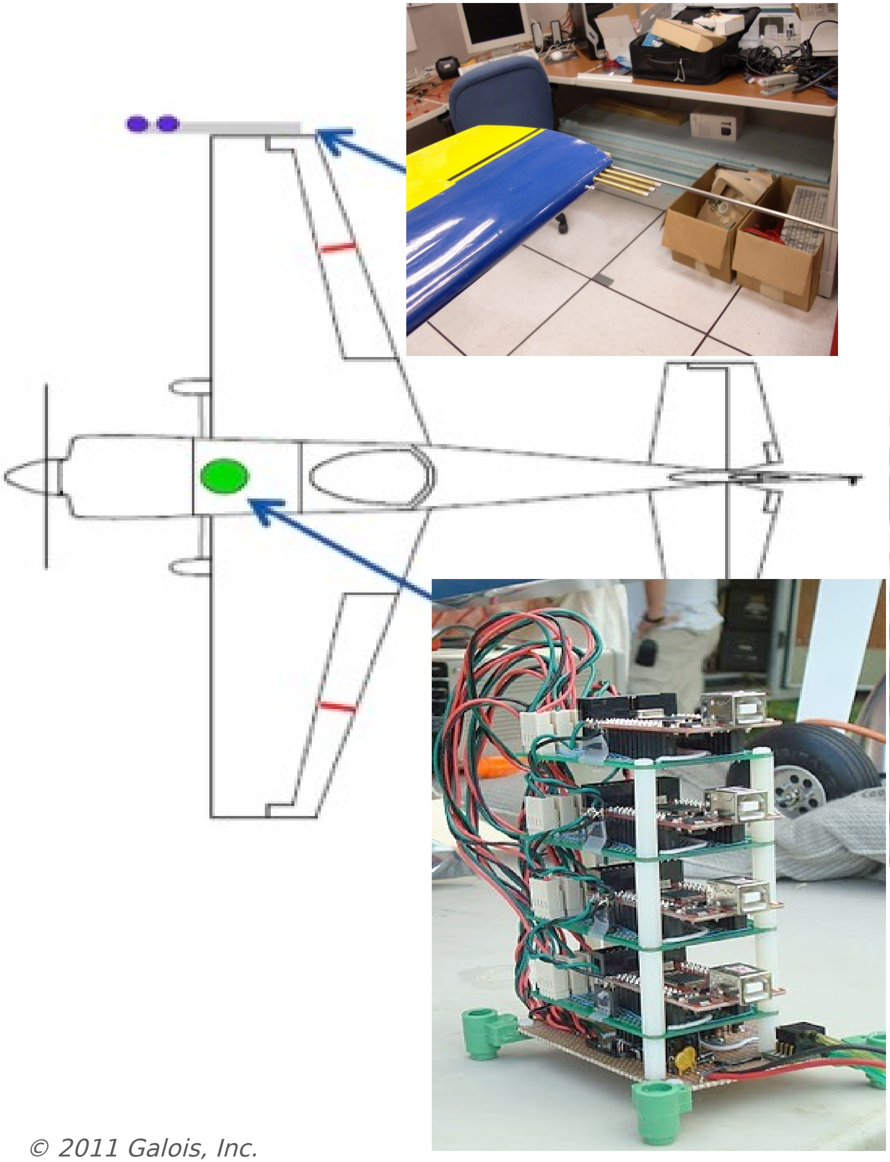
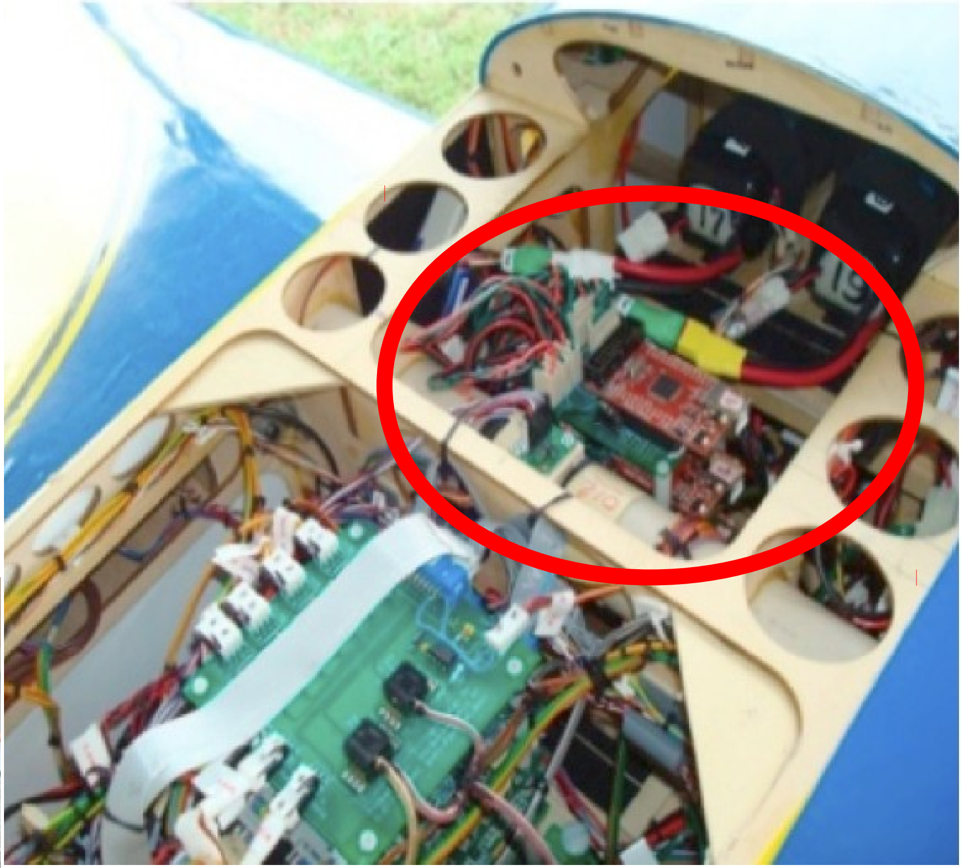
Aircraft Configuration
Edge 540T-R2





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Copilot Monitors

Introduced **software faults** to be caught by Copilot monitors:

- Abrupt airspeed change: airspeed $\Delta > 12$ m/s
- Fault-management assumptions
  - Fault-management used the Boyer-Moore majority vote algorithm
  - Check agreement between the voted values

    Uses coordinating distributed monitors
- Subsequent flights:
  - Ground-station communication protocol
  - Other sensors

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Monitoring Results

- Monitoring approach did not disrupt the FaCTS properties of the observed system
  - Under ~100 C expressions per monitor
  - Binaries on the order of 10k
- Monitoring via sampling works for periodic tasks
- *Next time*: didn’t think to monitor for a taped pitot tube!

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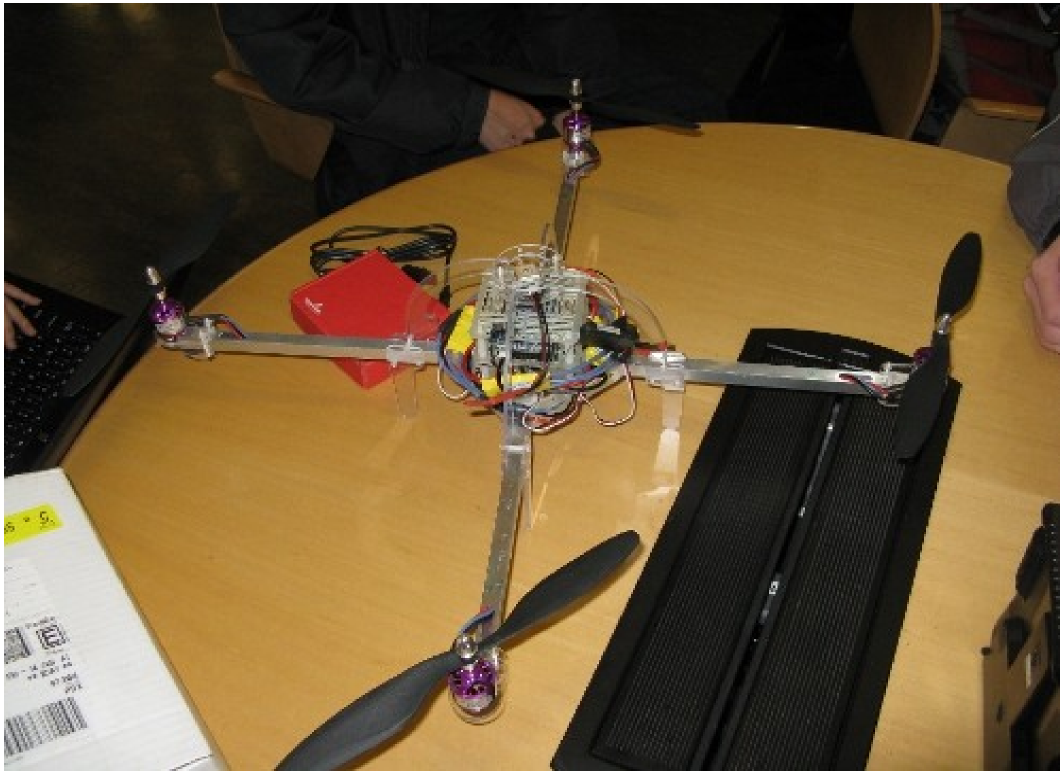
Future Work Test-Bed

In collaboration with Portland State University

- ArduPilot autopilot
- Altitude hold (barometer & sonar)
- Position hold (GPS magnometer)
- Collision avoidance (infrared)
- Stabilization (gyroscope)
- Battery monitoring



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Download, Develop, Use

http://leepike.github.com/Copilot/

BSD3

leepike/Copilot @ GitHub

http://leepike.github.com/Copilot/

Fork me on GitHub

Copilot

A (Haskell DSL) stream language for generating hard real-time C code.

Can you write a list in Haskell? Then you can write embedded C code using Copilot.
Here's a Copilot program that computes the Fibonacci sequence (over Word 64s) and tests for even numbers:

```
fib :: Streams
fib = do
  "fib" .= [0,1] ++ var "fib" + (drop 1 $ varW64 "fib")
  "t" .= even (var "fib")
    where even :: Spec Word64 -> Spec Bool
          even w = w `mod` const 2 == const 0
```

Copilot contains an interpreter, a compiler, and uses a model-checker to check the correctness of your program. The compiler generates constant time and constant space C code via Tom Hawkin's Atom Language (thanks Tom!). Copilot is specifically developed to write embedded software monitors for more complex embedded systems, but it can be used to develop a variety of functional-style embedded code.

Executing

```
> compile fib "fib" baseOpts
```

generates fib.c and fib.h (with a `main()` for simulation---other options change that). We can then run

```
> interpret fib 100 baseOpts
```

to check that the Copilot program does what we expect. Finally, if we have CBMC installed, we can run

```
> verify "fib.c"
```

to prove a bunch of memory safety properties of the generated program.

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Future Work

- The steering problem (mode change)

  Right now: escape to raw C

- Automated fault-tolerant monitor generation

  Monitors need 10^{-9} failures/hour reliability, too!

- Timing analysis: to monitor property *p*, need to sample at rate *r*

- Security monitoring for embedded systems

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Conclusions

- Problem space: hard real-time embedded C
  - The FaCTS: Functionality, Certifiability, Timing, SWaP
  - Approach: monitoring by periodic sampling

- The eDSL approach

  A path to fast, reliable compilers and languages

- *Nobody* watches the watchmen

  Prove/test/verify your compiler is correct

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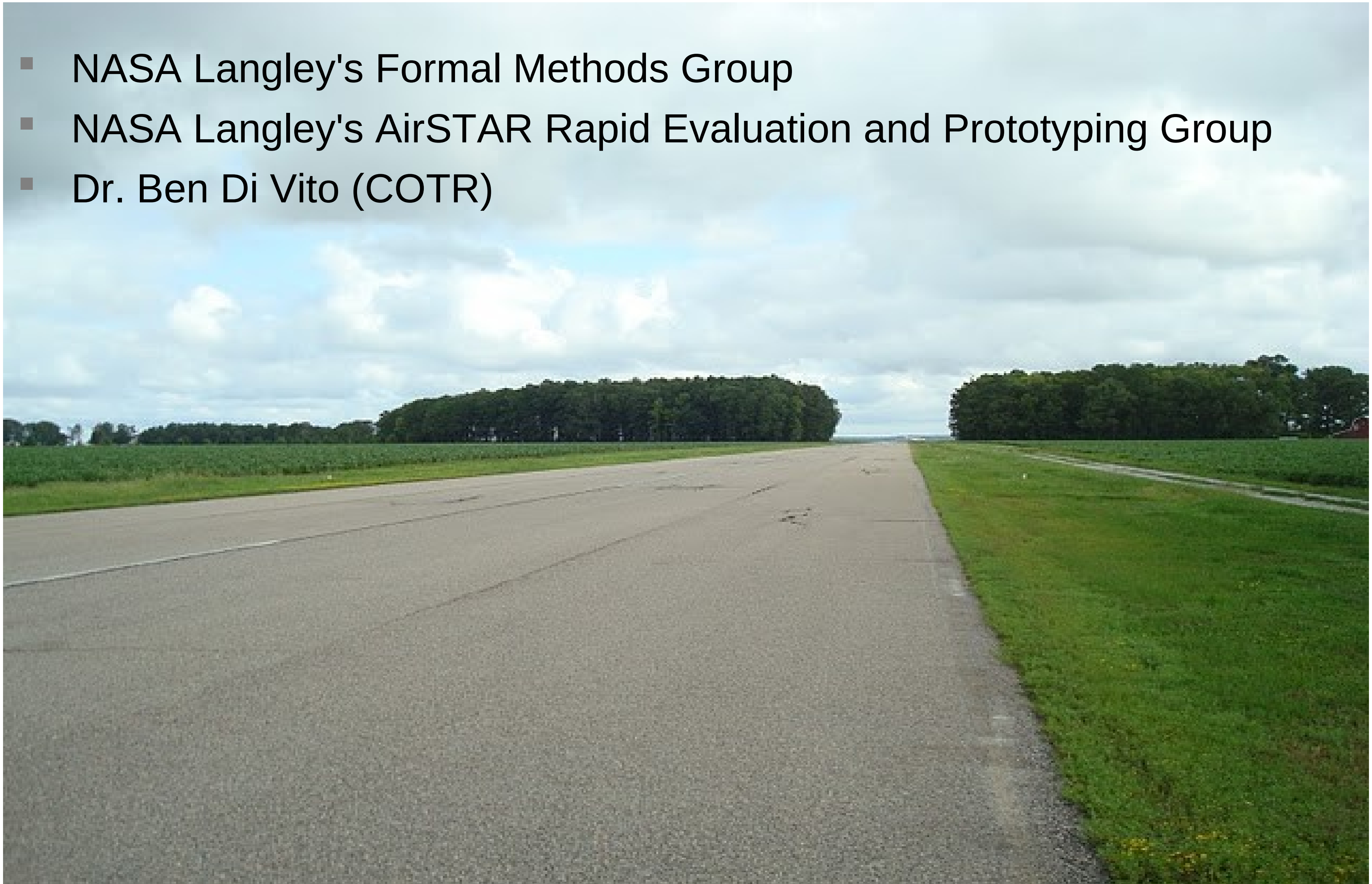
Thanks

- NASA Langley's Formal Methods Group
- NASA Langley's AirSTAR Rapid Evaluation and Prototyping Group
- Dr. Ben Di Vito (COTR)



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Appendix

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Monitoring By Sampling

Without inlining monitors, we must sample:

- Property (011)*
- False positive (monitor misses an fault):
  - Values are 011**1**011 but sampling 011011
- False negative (monitor signals a fault that didn't occur):
  - Values are 011011 but sampling 011**1**011
- Observation: with fixed periodic schedule and shared clock
  - False negatives impossible
    - We don't want to re-steer an unbroken system
  - False positives possible, but requires constrained misbehavior

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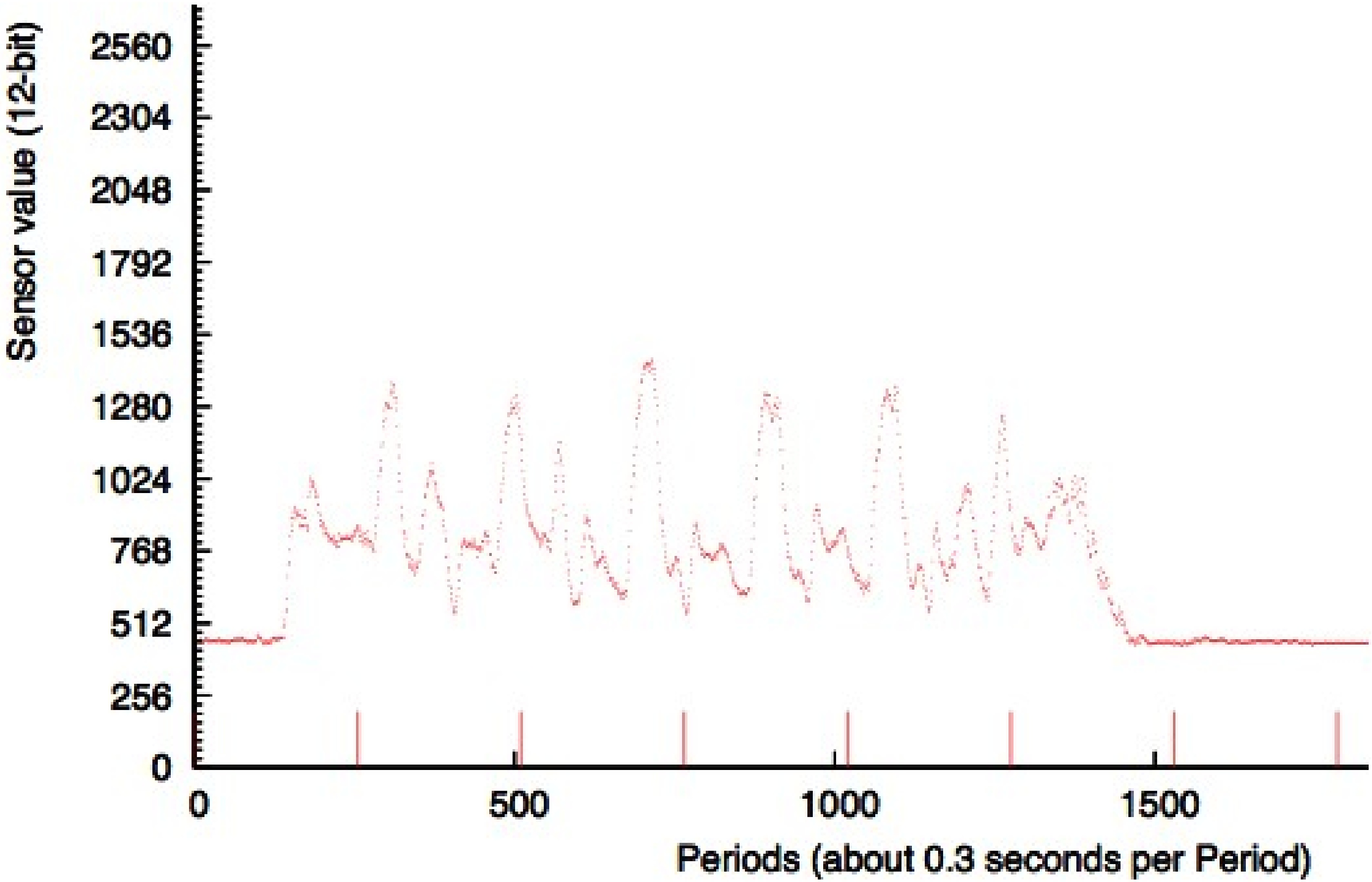
Pitot Data



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- Gui
- --> Lustre
- Scheduling on ARINC 653
- Rushby: Liam(sp? flight) the control sampling/smoothing data
- Overflow vars monitoring
- level C system level A monitor -- DO178B

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Stream Semantics (Append)

all operators are lifted in Copilot

(Copilot)

```
let x = varW64 in
    x .= [0, 1, 2] ++ x + 3
```

(Haskell)

```
f [0, 1, 2]
   where f :: [Word64] -> [Word64]
         f x = x ++ f (map (+3) x)
```

```
x = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
x = [0, 1, 2]
          ⇓      (+3)
    [3, 4, 5]
          ⇓      (+3)
    [6, 7, 8]
       ...
```

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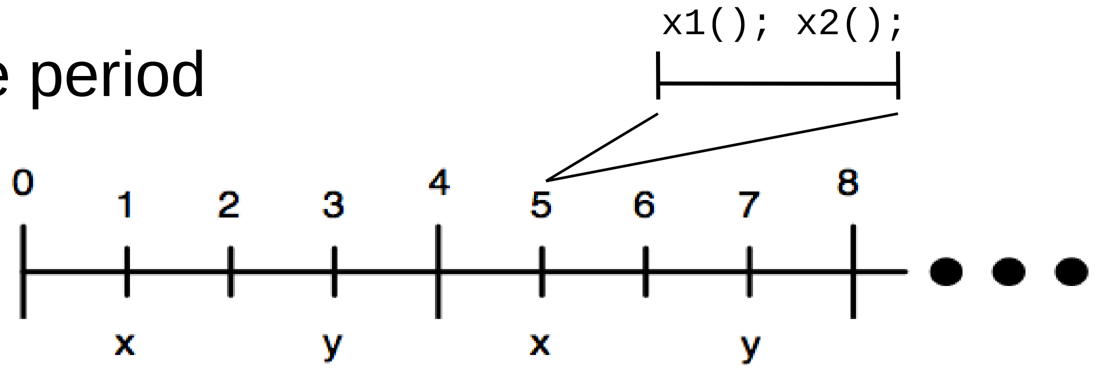
Timed Semantics

- **Period**: duration between discrete events
- **Phase**: offsets into the period
- Example:
  - x: period 4 phase 1
  - y: period 4 phase 3



- Copilot ensures synchronization between streams
  - Assuming synchronization of phases in distributed systems: no non-faulty processor reaches the start of phase *p*+1 until every non-faulty processor has started phase *p*

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Timed Semantics

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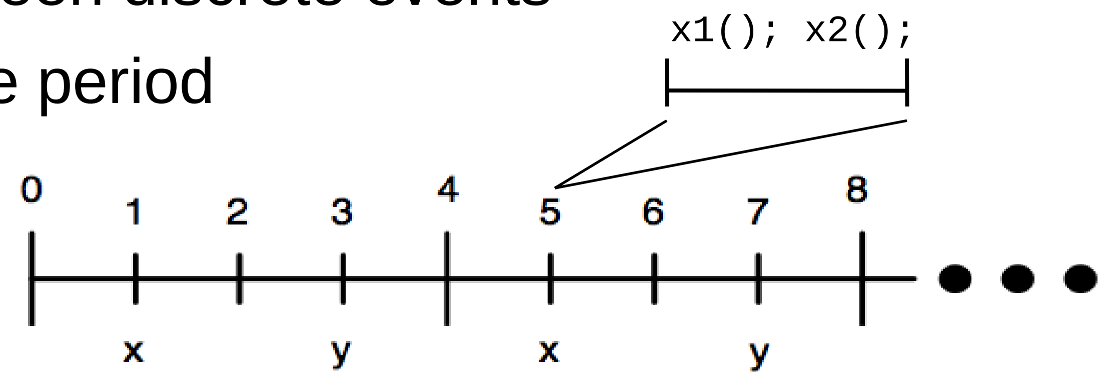

- Copilot ensures synchronization between streams
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Stream Semantics (Append)

all operators are lifted in Copilot

```
let x = varW64 in
    x .= [0, 1, 2] ++ x + 3                    (Copilot)
f [0, 1, 2]                                    (Haskell)
   where f :: [Word64] -> [Word64]
         f x = x ++ f (map (+3) x)
x = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
x = [0, 1, 2]
          ⇩       (+3)
    [3, 4, 5]
          ⇩       (+3)
    [6, 7, 8]
          ...
```

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Stream Semantics (Drop)

```
x .= [0, 1, 2] ++ x + 3
y .= drop 2 x

x = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
y = 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
```

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Stream Semantics (Drop)

```
x .= [0, 1, 2] ++ x + 3
y .= drop 2 x

x = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
y = 2, 3, 4, 5, 6, 7, 8, 9, 10 ...
```

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Sample Code Generated (Incomplete)

state-update function for *trigger* stream

```
/* engine.updateOutput__trigger */
static void __r0() {
  bool __0 = true;
  bool __1 = engine.tmpSampleVal__shutoff_2;
  bool __2 = ! __1;
  float __3 = 2.3F;
  uint64_t __4 = 0ULL;
  uint64_t __5 = engine.outputIndex__temps;
  uint64_t __6 = __4 + __5;
  uint64_t __7 = 4ULL;
  uint64_t __8 = __6 % __7;
  float __9 = engine.prophVal__temps[__8];
  float __10 = __3 + __9;
  uint64_t __11 = 2ULL;
  uint64_t __12 = __11 + __5;
  uint64_t __13 = __12 % __7;
  float __14 = engine.prophVal__temps[__13];
  bool __15 = __10 < __14;
  bool __16 = __2 && __15;
  bool __17 = ! __16;
  if (__0) {
  }
  engine.outputVal__trigger = __17;
}
```

```
engine :: Streams
engine = do
      ...
   trigger =     (var overTempRise)
             ==> (extB shutoff 2)
```

external variable sample function

```
/* engine.sample__shutoff_2 */
static void __r6() {
  bool __0 = true;
  bool __1 = shutoff;
  if (__0) {
  }
  engine.tmpSampleVal__shutoff_2 = __1;
}
```

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Copilot Language Restrictions

Design goal: make memory usage constant and "obvious" to the programmer

- No anonymous streams
  - Compiler doesn't have to worry about sharing
- No lazily-computed values
  - E.g. `x .= [0] + x + 1`
    `y .= drop 2 x`
- Other restrictions (see paper)
- Upshot: "WYSIWYG memory usage"
  - Memory constrained by number of streams
  - Memory for each stream is essentially the LHS of ++
  - Doesn't include stack variables

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Timing Info & Expression Counts

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Timing info

```
Period  Phase  Exprs  Rule
------  -----  -----  ----
     3      0     18  engine.updateOutput__trigger
     3      0     14  engine.updateOutput__overTempRise
     3      0      3  engine.update__temps
     3      1      7  engine.output__temps
     3      1      2  engine.sample__temp_1
     3      2      6  engine.incrUpdateIndex__temps
     3      2      2  engine.sample__shutoff_2
                 -----
                    52
Hierarchical Expression Count
```

Expression count

```
  Total   Local     Rule
  ------  ------    ----
      52       0    engine
       6       6      incrUpdateIndex__temps
       7       7      output__temps
       2       2      sample__shutoff_2
       2       2      sample__temp_1
      14      14      updateOutput__overTempRise
      18      18      updateOutput__trigger
       3       3      update__temps
```

helps with WCET analysis

```
Generated engine.c and engine.h
Moving engine.c and engine.h to ./  ...
Calling the C compiler  ...
gcc ./engine.c -o ./engine -Wall
```

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Example Copilot Specification

“If the temperature rises more than 2.3 degrees within 2 seconds, then the engine has been shut off.” (period == 1 sec)

```
engine :: Streams
engine = do
  -- external vars
  let temp     = extF "temp" 1
  let shutoff  = extB "shutoff" 2
  -- Copilot vars
  let temps    = varF "temps"
  let overTemp = varB "overTemp"
  let trigger  = varB "trigger"

  temps    .= [0, 0, 0] ++ temp
  overTemp .= drop 2 temps > 2.3 + temps
  trigger  .= overTemp ==> hutoff
```

phases to sample in

initial “don’t care” values

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Usage

- `compile spec "c-name" [opts] baseOpts`
- `interpret spec rounds [opts] baseOpts`
- `test rounds [opts] baseOpts`
  - quickChecking the compiler/interpreter
- `verify filepath int`
  - SAT solving on the generated C program
- `help (commands and options)`
- `[spec]` (parser)
- Opts (incomplete list):
  - C trigger functions
  - Ad-hoc C code (library included for writing this)
  - Hardware clock
  - Verbosity
  - GCC options

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Runtime Monitoring: What's New?

- Not new:
  - One-out-of-two systems
  - Error-checking codes
  - Distributed fault-tolerance
  - Built-in test

Common source of faults

- New(er) ideas:
  - Domain-specific languages for monitoring
  - High-assurance monitors
  - **SW as a system component**

    Decompose monitoring and controlling

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Types

- Types: Int & Word (8, 16, 32, 64), Float, Double
- Each stream has a unique inferred type:

```
let x = varW64 "x"
x .= [0, 1] ++ x + 3
```

inferred types

- Casting
  - Implicit casting is a type-error

    Won't compile

```
let x = varW64 "x"
let y = varW32 "y"
x .= y
```

  - Explicit casting guarantees:
    - signs never lost (no `Int --> Word` casts)
    - No overflow (no cast to a smaller width)

```
let x = varB "x"
let y = varI32 "y"
x .= [True] ++ not x
y .= cast x + 4
```

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