BLECH –
A SYNCHRONOUS LANGUAGE FOR EMBEDDED REAL-TIME PROGRAMMING

KEYNOTE, WCET 2019

FRANZ-JOSEF GROSCH

JOINT WORK WITH FRIEDRICH GRETZ

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Bosch
Technology to enhance quality of life

Bosch – a global network
Research and Development 2018

4 business sectors

Mobility Solutions

Industrial Technology

Consumer Goods

Energy & Building Technology

Bosch

In 2018
78.5 billion €
Company's sales

In 2018, Bosch invested
7.3 billion €
in research and development

The international research network of Corporate Research has
12 locations in 8 countries

130
Bosch research and development locations worldwide

410,000
Bosch associates worldwide

Research and development

In 2018
392,4 million €
were invested in Corporate Research & Bosch Center for Artificial Intelligence

69.000
Bosch researchers and developers worldwide

~1.800
associates in Corporate Research & Bosch Center for Artificial Intelligence

Corporate Research & BCAI

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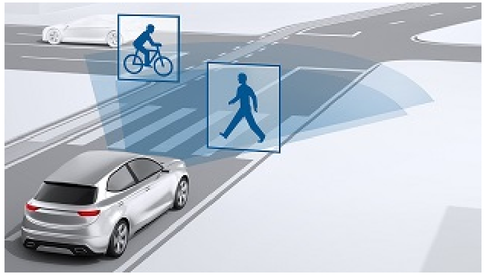
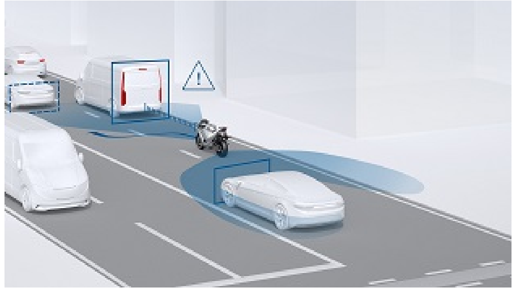
Technology to enhance quality of life

Some examples

- Driver assistance and automated driving





- Powertrain systems and electrified mobility

- Home appliances

- Power tools

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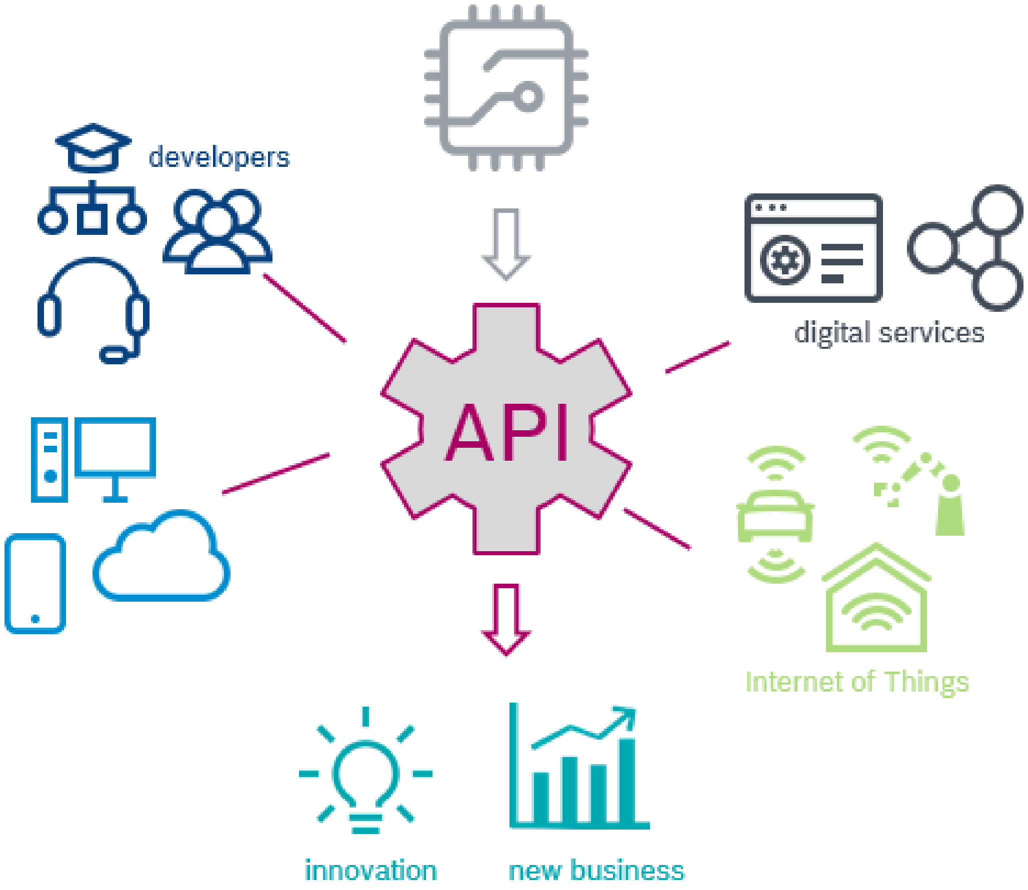
Bosch "Things" in a connected world
The importance of embedded software



- Bosch's biggest strength in the IoT ecosystem are the Bosch "Things"
- These devices and physical products cover a multitude of domains
- Each with high market penetration typically among the TOP 3
- "Bosch is a giant in embedded software" (Dr. Volkmar Denner, CEO)

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The structure of embedded software
Timing behaviour expressed via the environment

- "One-step" functions …

  `f()` no inputs, no outputs, operates on global variables

- … composed in operating system tasks

  `f() g() h()` sequentially ordered

- … activated periodic (time-triggered), sporadic (event-triggered) or even rate-adaptive

  `IRQ 10 k() l()`
  `10 msec f() g() h()`
  repeated on clock-tick or on interrupt

- … scheduled according to priorities

  `8: 1 msec n()`
  `5: IRQ 10 k()`
  `2: 10 msec g()`

  High priority task pre-empts lower
  task switch is a function call
  only one stack for all tasks

More details: *Real world automotive benchmark for free*, Kramer et al., 2015

The structure of embedded software
Questions causing trouble

- One-step functions
  - How do we manage state between two activations?
  - How do we reason about the behaviour of a function over repeated activations?
- Single task composition
  - Which function is writing what variable and when?
  - What is a suitable order of functions in a task?
  - How do we reason about combinations of functions in a task?
- Execution of parallel tasks
  - How is the dataflow between tasks?
  - How do we reason about combinations of functions in parallel tasks?

Do we need a programming language better suited to embedded requirements?

Why a new language?
Build a better tool!

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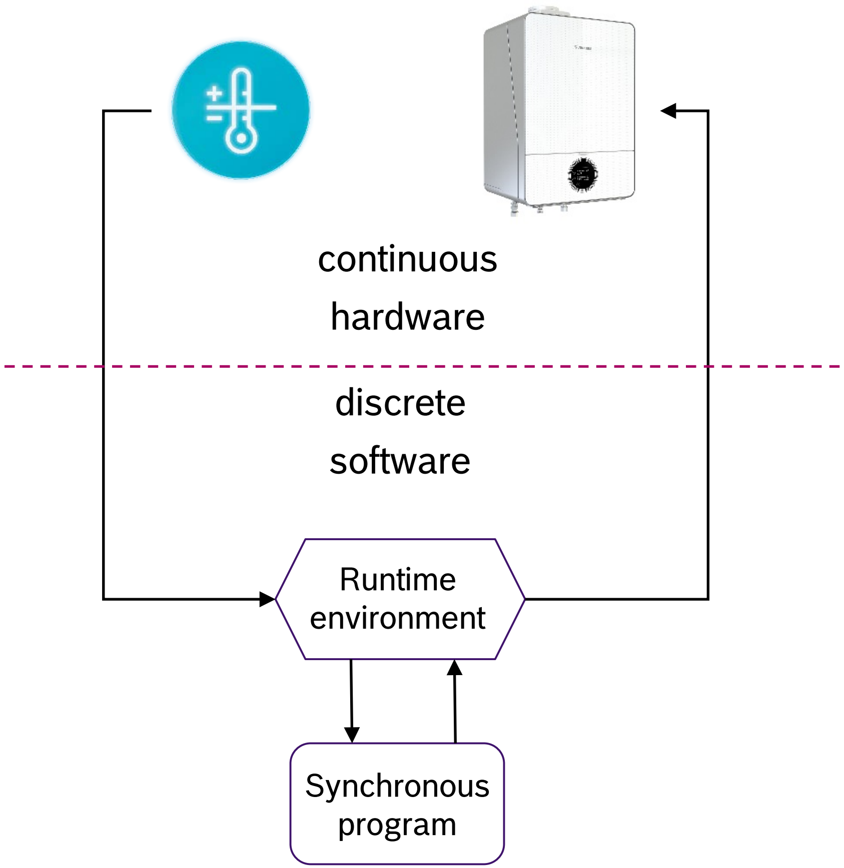
Should the language be synchronous?
The synchronous paradigm



- Environment communicates asynchronously with physical world, drives synchronous programs
- A program is executed is *steps*
  - A sequence of steps is called a thread (we prefer trail)
- Assume a step takes no time (happens instantaneously)
  - No change of input data throughout computation
- Sequences of steps can be composed concurrently
  - Accesses to shared data happen in a deterministic, causal order

Do we need a new synchronous language?
Available alternatives do not fulfill our requirements

▶ Céu	purely event-triggered, no causality, soft-realtime
▶ Esterel	no longer supported, focus on control flow and coordination
▶ Lustre	not imperative, focus on data flow, difficult to transfer
▶ Quartz	focus too broad: specification of hardware and software

Create a synchronous imperative language - Blech

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Goal: Synchronous control for an imperative language

Express behaviour over time

```
function times2 (x: int32) returns int32
    return x * 2
end

activity A (inA: int32)(outA: int32)
    repeat
        await true
        outA = times2(inA)
        if outA >= 0 then
            await inA > 0
        end
        outA = times2(inA)
    until outA < 0 end
end
```

- Start with a safe imperative core language
  - Focus on readability
  - Safe saturation arithmetic, precisely sized types
  - No global variables
- Add a statement to execute in steps
  - `await <condition/event/clock tick>`
  - `await true` ⇔ `await tick`
- Introduce two kinds of subprograms
  - `function` – one step, no await
  - `activity` – multiple steps, at least one await
- Introduce two kinds of parameter lists
  - Inputs – read only
  - Outputs – read/write

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How is this executed?
Stackless execution in macro steps

Time steps	inA	outA
t_{i+1}	7	14
t_{i+2}	-1	14
t_{i+3}	5	28
t_{i+4}	-2	-8

```
function times2 (x: int32) returns int32
    return x * 2
end

activity A (inA: int32)(outA: int32)
    repeat
        await true
        outA = times2(inA)
        if outA >= 0 then
            await inA > 0
        end
        outA = times2(outA)
    until outA < 0 end
end
```

A standard imperative core language implies
Sequentially Constructive Concurrency, Hanxleden et al., 2013

How is this compiled?
Functions called on every step

```
// C-like pseudocode

void mainloop () {
    step_of_A();
    ...
}
```

```
void step_of_A () {
    // restore code location

    // check await condition

    // execute corresponding computation

    // save location for next reaction
}
```

Boilerplate state management code

Hard to code manually

“Business” logic

Interesting part of the program

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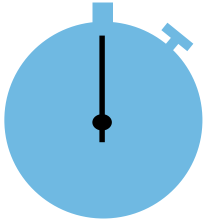
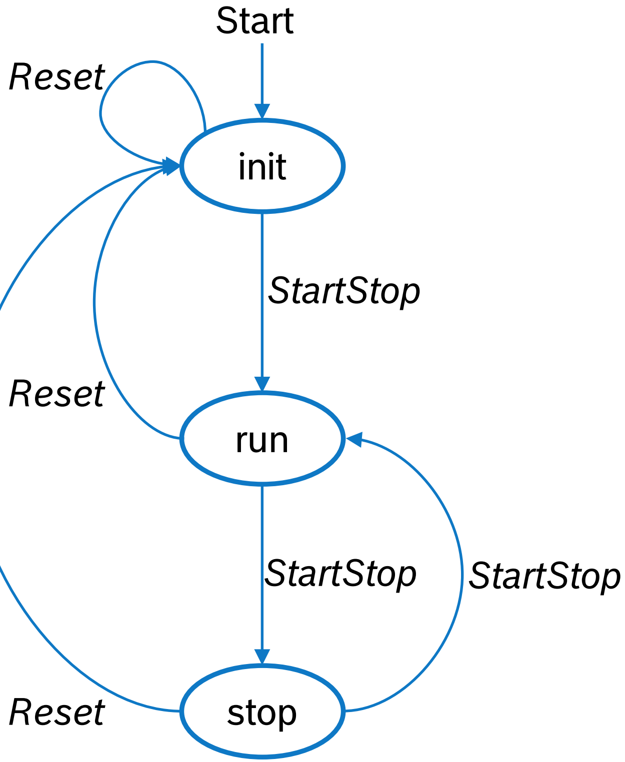
How is this developed?
Mode transitions as synchronous control flow






```
activity stopWatchControl (isPressedStartStop: bool,
                           isPressedReset: bool)
                          (display: Display)
   reset when isPressedReset before
      // init
      display:resetToZero()
      if not isPressedStartStop then
         await isPressedStartStop
      end
      repeat
         // run
         repeat
            await true
            display:increment()
         until isPressedStartStop end
         // stop
         await isPressedStartStop
      end
   end
end
```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How is this composed?

Concurrent composition of behaviours over time

```
/// Main Program
@[EntryPoint]
activity Main (isPressedStartStop: bool,
               isPressedReset: bool)
   var display: Display
   cobegin // control
      run StopWatchController(isPressedStartStop,
                              isPressedReset)
                             (display)
   with // render
      repeat
         display:show()
         await true
      end
   end
end
```

- Execution model
  - Concurrent behaviours run in synchronized steps
- Causal order
  - first, update display data
  - second, show display
- Code generation
  - sequential code
  - Statically ordered by the compiler

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Combine behaviours over time
Concurrent composition with improved readability and flexibility

```
activity A(inA: int32)(outA: int32)
...
end

activity B(inB: int32)(outB: int32)
...
end

activity main()
    var x: int32
    var y: int32
    cobegin weak
        run A(x)(y)
    with
        run B(y)(x)
    end
end
```

- Add a control flow statement for concurrent composition
  - Focus on readability: `cobegin ... with ... with ... end`
  - Usable as an orthogonal statement
- Entering `cobegin` blocks (also called fork)
  - Execute multi-step trails (also called threads) concurrently
- Exiting `cobegin` blocks (also called join)
  - Terminate all trails in the same step
  - Strong trails run to their end, `weak` trails can be terminated early
- Execute in causal order of statement sequences
  - Concurrent `cobegin` blocks compile to sequential code
  - Causality analysis does not look into activities and functions
- Express parallel and/or
  - `cobegin ... with ... end                // parallel and`
  - `cobegin weak ... with weak ... end  // parallel or`

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Deterministic sequential execution of concurrent code

Non-global causality analysis

```
activity main()
    var x: int32
    var y: int32
    cobegin weak
        run A(x)(y)
    with
        run B(y)(x)
    end
end
```

Error: causality cycle

Solve causality cycle

```
activity main ()
var x: int32
var y: int32
    cobegin weak
        run A(x)(y)
    with
        run B(prev y)(x)
    end
end
```


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How is this compiled?

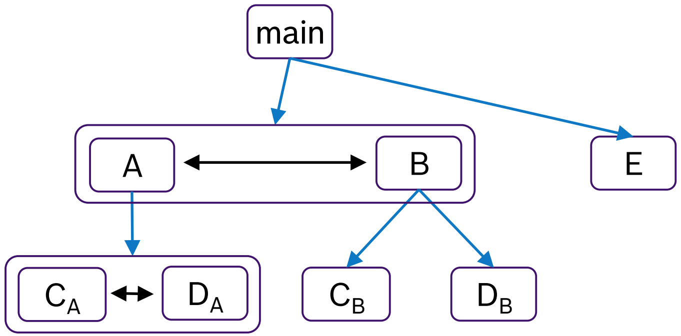
Local variables stored in global memory

```
activity A(inA: int32)(outA: int32)
   cobegin
      run C()
   with
      run D()
   end
end

activity B(inB: int32)(outB: int32)
    run C()
    run D()
end

activity main ()
    var x: int32
    var y: int32
    cobegin weak
       run A(x)(y)
    with
       run B(prev y)(x)
    end
    run E()
end
```

Call graph



"Stack views"

main	main	main
A	A	E
C_A	C_A	
D_A	D_A	
B	B	
C_B	D_B	

Pre-computed "cactus stack"

```
struct A{
  /* A's locals */
  struct C c;
  struct D d;
};
struct B{
  /* B's locals */
  union {
    struct C c;
    struct D d;
  }
};
struct Main{
  /* Main's locals */
  union {
    struct {
      struct A a;
      struct B b;
    } a_with_b;
    struct E e;
  };
};

struct Main _Globals;
```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Software structure and design

Structured data types, references, objects, modules

```
struct Value
    var first: int32
    var second: float32
end

ref struct MyType
    var flag: bool
    var ref value: Value // initialised at declaration
with
    const c: int32 = 42     // compile time constant

    param p: float32 = 9.81 // hex file constant

    function f() returns int32       // static subprogram
    end

    mutating activity mt:actMethod() // method subprogram
        mt.value.first = f() // deref 'value' taken automatically
    end
end
...
    var v: Value = {first = 1} // second gets default value
    var mt: MyType =
        {flag = true, value = v} // ref 'v' taken automatically
```

- Introduce two kinds of types
  - value types
  - reference types
- Introduce structured value types
  - Atomic for causality analysis
  - Useful for data exchange
  - `prev` and `next` allowed, shallow copying
- Introduce reference types
  - Atomic for causality analysis
  - Useful for structuring
  - Non-cyclic dependencies required
  - Bound during instantiation
- Introduce modules
  - Unit of separate compilation
  - Non-cyclic import hierarchy required

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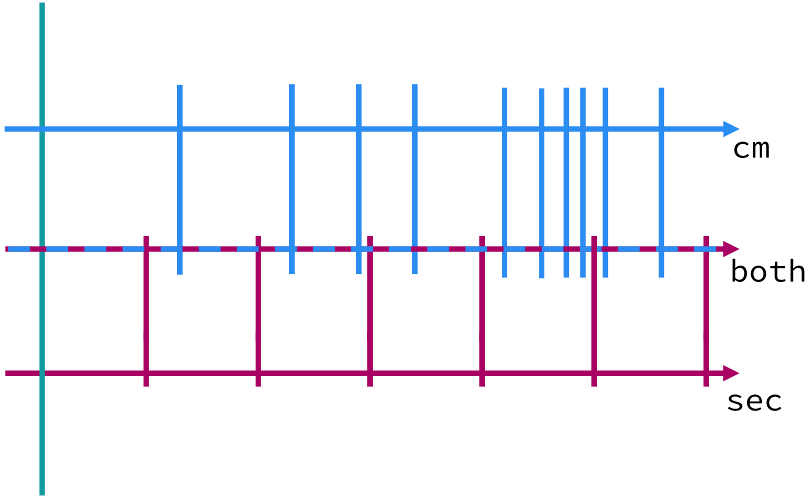
Clocks – a way to express multi-form time

Speed – a synchronous “Hello world”




```
clock cm
clock sec
clock both = cm join sec
```

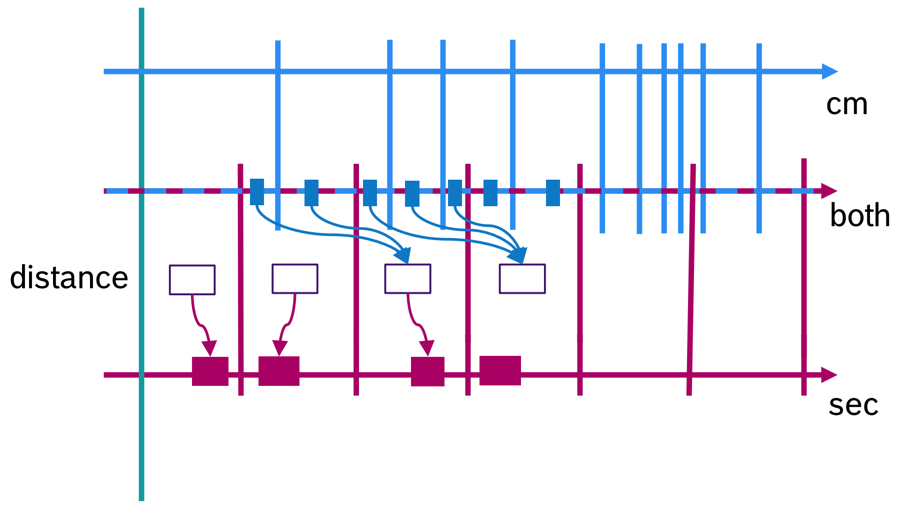
```
activity countingCmBetweenSeconds()(distance: int32) on both
    repeat await true  // any tick
        if tick cm then
            distance = distance + 1
        elseif tick sec then
            distance = 0
        end
    end
end

activity updatingSpeed(distance:int32)(speed: int32) on both
    repeat await tick sec
        speed = distance
    end
end

activity startup() on both
    var distance: int32 = 0
    var speed: int32 = 0
    cobegin
        run countingCmBetweenSeconds()(distance)
    with
        run updatingSpeed(distance)(speed)
    end
end
```

Parallel programming with clocks

Logical execution time and clock refinement




```
clock cm
clock sec
clock both = cm join sec
```

From control models to real-time code using Giotto, Henzinger et al., 2003

Clock refinement in imperative synchronous languages, Gemünde, Brandt, Schneider, 2013

```
activity countingCmBetweenSeconds()(distance: int32) on both
   repeat await true  // any tick
      if tick cm then
         distance = distance + 1
      elseif tick sec then
         distance = 0 end
   end
end

activity updatingSpeed(distance:int32)(speed: int32)
   repeat await true
      speed = distance
   end
end

activity startup()() on sec
   var speed: int32 = 0
   var distance: int32 = 0
   cobegin
      on both run countingCmBetweenSeconds()( next distance)
   with
      run updatingSpeed(distance)(speed)
   end
end
```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Simplified static analysis
The compiler knows and guarantees static properties

- No recursion
- No pointers
- No address arithmetic
- No dynamic allocation
- No concurrent write conflicts
- No dynamic concurrency
- No dynamic parallelism
- No global variables
- No undefined values
- No programmer-defined locking
- Separate compilation

- Predictable memory usage
- Predictable execution time
- Always one writer multiple readers
- Statically known end-to-end latencies
- Statically known number of clocks
- Known, possible number of tasks
- Predictable synchronisation effort
- Easier task deployment
- Easier variable mapping
- Room for optimisation in code generation
- Reduced need for whole program analysis

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“Bosch is a giant in embedded software” (Dr. V. Denner, CEO)
Wishlist for an embedded real-time programming language

Core Business
“Things” driven by embedded software

- Hybrid: Time-driven and event-driven
- Predictable and deterministic
- Synchronous concurrency
- Hard real-time
- Bounded memory usage and execution time
- Easy integration of C code
- Prepared for multi-core
- Explicit control of deployment and variable placement
- Compile-time mechanisms for structuring and variants
- Safe shared memory
- Safe type system
- Expressive and productive
- A “real cool” development environment

Elevate embedded real-time programming
Bridging the gap between models and C code

Analysis & Modelling

ASCET-DEVELOPER   SCODE-CONGRA   Simulink®   MODELICA   Scade®

Simulation & Transformation

Design & Implementation
- Real-time requirements
- Reactive concerns
- Software design
- Built-in concurrency
- Deterministic parallelism

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Legacy Software

Runtime & Drivers

Verification & Testing
- Assertion checking
- Unit testing
- Debugging
- Closed-loop simulation

Deployment

C Task   C Task   C Task   C Task   C Task

Hardware-in-the-loop

Bosch products

Field testing

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Elevate embedded real-time programming
Our embedded software vision

- Take care of multi-disciplinary engineering
- Express timing behavior in the program (not in the environment)
- Enable clean embedded software architectures
- Re-enable reasoning about parallel programs
- Improve productivity, agility, maintainability, testability, modularity, abstraction
- Support and attract software professionals

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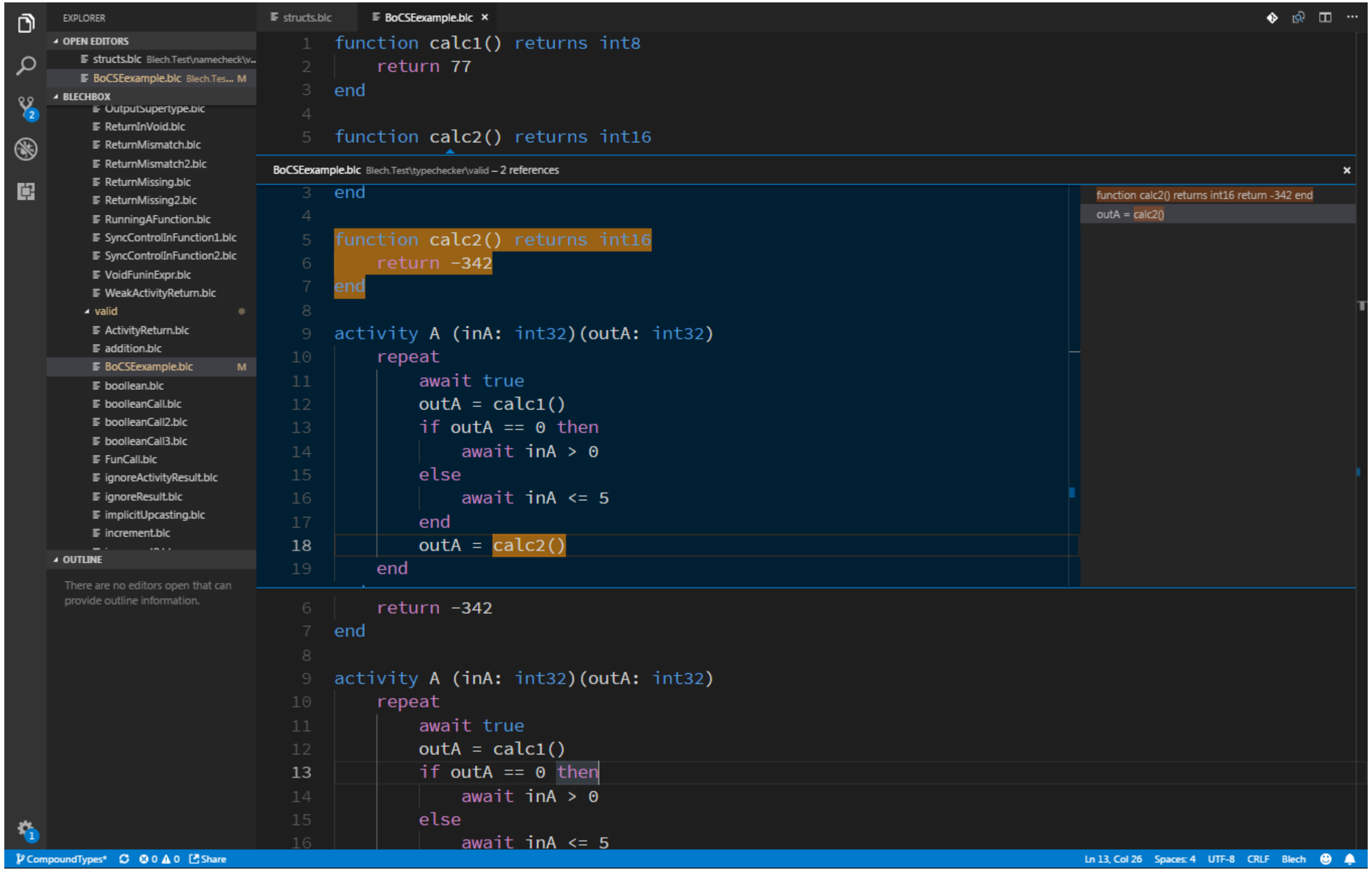
First steps on a “cool” development environment

A Blech Language Server used with Visual Studio Code



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Where we stand
... and where to go

- We have a clear vision of Blech's features ... we are open for discussion
- We are a small team ... we are open for cooperation
- We implement the compiler, the language server and the build system in F# ... we prepare to go open-source

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THANK YOU

www.bosch.com