Hardware-near Programming in the Common Language Infrastructure

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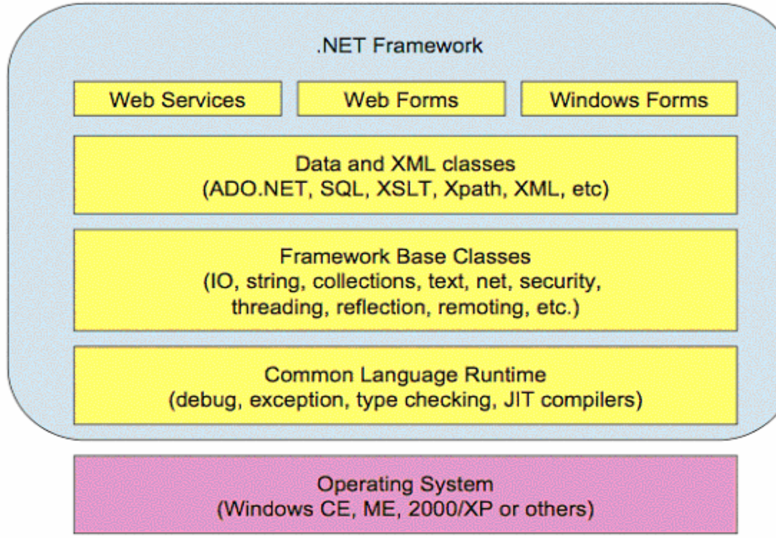
ISORC 2007
7-9 May, 2007
Santorini Island, Greece

Roadmap

- The Common Language Infrastructure
- Real-time.Net Project
- GCC Common Intermediate Language (CIL) Front-end
- Hardware-near programming
  - Direct-memory access
  - Interrupt handling
  - Support for Implementing Concurrency
- Conclusions

The Common Language Infrastructure

- Open specification developed by Microsoft
  - Describes executable code
  - Runtime environment
  - Describes core of the Microsoft .NET Framework
- Standardized by ISO/ECMA:
  - ISO/IEC 23271
  - Standard ECMA-335



.NET Framework

Web Services

Web Forms

Windows Forms

Data and XML classes
(ADO.NET, SQL, XSLT, Xpath, XML, etc)

Framework Base Classes
(IO, string, collections, text, net, security, threading, reflection, remoting, etc.)

Common Language Runtime
(debug, exception, type checking, JIT compilers)

Operating System
(Windows CE, ME, 2000/XP or others)

- Common Language Runtime (CLR) is Microsoft's commercial implementation of the CLI
- Open source implementations: Mono, Portable.Net

C# and CLI for Real-Time Systems

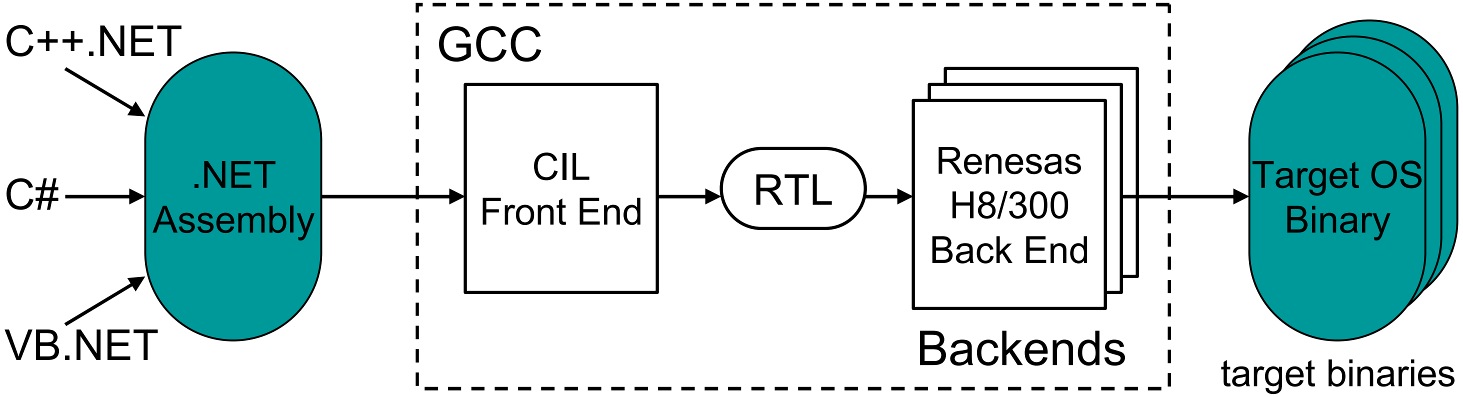
- Higher-level programming languages induce higher developer productivity
  - Programming errors never result in system crashes because of predictable nature of sandbox-mode execution of CLI instructions
  - due to the support for rapid prototyping, simulators for targets can be created more easily.
  - Usage standard library functions of the CLI minimizes code for target-specific hardware.
- Find a way to run CLI intermediate language (IL) code on the target
- Find a way to integrate the CLI program with the “special” hardware of the target
- Find a way to provide real-time guarantees to developers of applications for the target

ECMA CLI for Real-Time Systems

- **Just-in-time compilation** causes hard-to-predict execution times for method execution
- **Garbage collection** freezes application code for potentially long time
- **Memory allocation actions**, such as object creation, vary depending on whether garbage collection is invoked to free unused memory for reuse
- No support for **hardware-near programming**
  - Direct Memory Access
  - Memory Mapped I/O
  - Interrupt Handling
  - Low-level access to registers (scheduler support)
- Limited **threading** model (semantics, priorities, policies, synchronization)

GCC Intermediate Language Front-End

- Modification the GNU Compiler Collection (GCC) to support compilation of IL code into target machine code
  - Compilation of each method in intermediate language into one function on assembler level
  - Symbolic execution to translate the stack machine instructions into GCC's internal statement representation (GNU compiler for Java (GCJ) approach)
  - GCC optimizes and compiles into assembler code



I/O Subsystem in Real-Time.Net

- Mapping hardware to the CLI’s object model
- Attributes (annotations) for marking fields for direct I/O address mapping
  - **`[MemoryAlias(addr)]`** for memory mapped I/O
  - **`[PortAlias(addr)]`** for port based I/O

```
[MemoryAlias(0xff82)]
static byte myMemoryLocation;

byte b = myMemoryLocation;
myMemoryLocation = ~0x42;
myMemoryLocation |= 0x23;
```

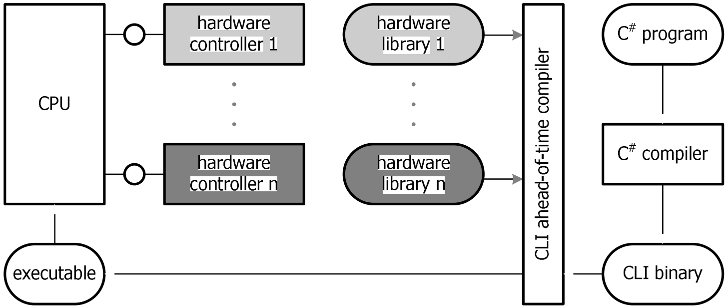
Structured Definition of Hardware

```
public struct Port{
    [MemoryAlias(0x00)]
    public byte
    DataDirectionRegister;
    [MemoryAlias(0x02)]
    public byte DataRegister;
}
```

```
public struct H8_3297{
    /* ... */
    [MemoryAlias(0xFFB5)]
    public static Port Port4;
    [MemoryAlias(0xFFB8)]
    public static Port Port5;
    /* ... */
}
```

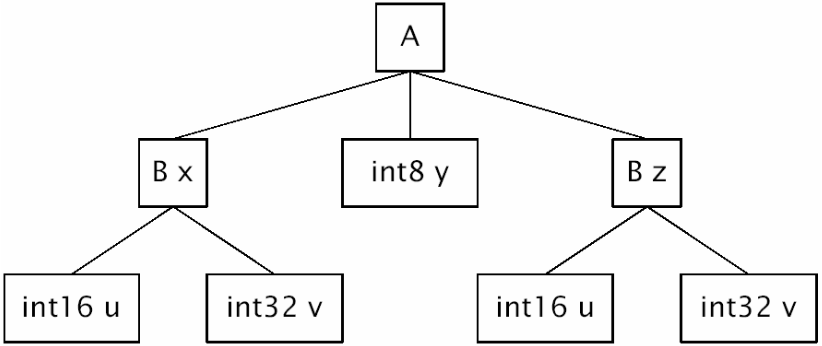
```
byte b = H8_3297.Port5.DataRegister;
H8_3297.Port5.DataRegister = ~0x42;
H8_3297.Port4.DataDirectionRegister |= 0x23;
```

- Hardware vendors implement library for their hardware
- Hardware access defined by vendor-specific struct



Rules for Memory/Port Aliases I

- Uniqueness: At most one alias attribute per field
- Validity: Addresses must be valid
- Fields the type of which is a *Closed Value Type* only
  - CVTs are value types that contain value types only
- Completeness
  - All fields in a type must have the same alias type
  - Static fields must have the same alias type as their type
- No access optimisation
- No memory management



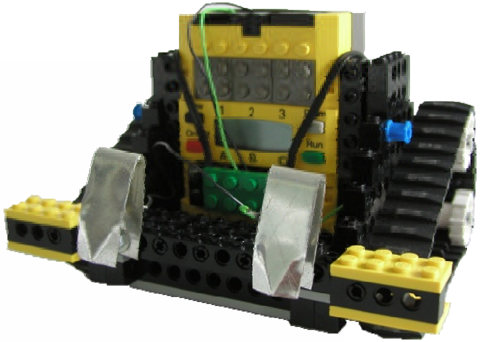
Rules for Memory/Port Aliases II

- Let *x* be the value attached to a field f by an alias attribute. If *f* is static, its address is *x*.
  - ldsflda f : loads x on the stack
- Otherwise, its address is the sum of *x* and the address of the field that *f* is a field of.
  - ldflda f : takes an address *a* from the stack and pushes *a+x*

Rules for Memory/Port Aliases III

- Let f be a MemoryAlias(x) attributed field the type of which is a built-in type of size *s*. Then, the memory block of size *s* starting at the alias address of *f* is never to be used for memory allocation. Accesses to f are to be redirected to its alias address:
    - ldsfld f : reads from address *x* and pushes that value on the stack
    - stsfld f : pops a value from the stack and writes it to address *x*
    - ldfld f : takes an address *a* from the stack, reads from address *a*+*x* and pushes that value on the stack
    - stfld f : takes an address *a* from the stack, then pops a value from the stack and writes it to address a+x
- Analogous for PortAlias

```
public static void Sound (ushort frequency)
{
        Off ();

  if (frequency < 31)
    return;

  H8_3297.Board.Timer8Bit.Channel0.ControlStatusRegister = 0x03;
  H8_3297.Board.Timer8Bit.Channel0.TimerCounter = 0x00;

  if (frequency <= 122)
  {
    H8_3297.Board.Timer8Bit.Channel0.ConstantRegisterA =
        (byte) ( (short) 7813 / frequency);

    H8_3297.Board.SerialTimerControlRegister &= 0xFE;
    H8_3297.Board.Timer8Bit.Channel0.ControlRegister = 0x0B;
  }
  else if (frequency <= 488)
  {
    H8_3297.Board.Timer8Bit.Channel0.ConstantRegisterA =
        (byte) (31250 / frequency);

    H8_3297.Board.SerialTimerControlRegister |= 0x01;
    H8_3297.Board.Timer8Bit.Channel0.ControlRegister = 0x0B;
  }
```



I/O Subsystem: Interrupts

- Interrupt vectors are `delegate` fields of type `void delegate InterruptHandler (void)`
- Interrupt handlers are `static` methods with `[InterruptHandler]` attribute
- Parts of immediate working context that is manipulated must be saved on entry and restored on exit of interrupt handlers method
- Immediate interrupt context must be restored at the end of interrupt handler methods
  - Our GCC frontend generates different return opcode “return from interrupt”
- Static functions for controlling interrupt hardware
  - Hardware.Cpu.Interrupts.DisableAll
  - Hardware.Cpu.Interrupts.EnableAll

Interrupt Handling Example (manufacturer)

```
[StaticDelegate]
public delegate void InterruptHandler ();

public struct VectorTable
{
  [MemoryAlias(0x06)]
  public InterruptHandler NonMaskableInterrupt;
}

public class Hardware
{
  [MemoryAlias(0x0000)]
  public static VectorTable VectorTable;
  [MemoryAlias(0xFFC3)]
  public static byte SomeRegister;
}
```

Interrupt Handling Example (programmer)

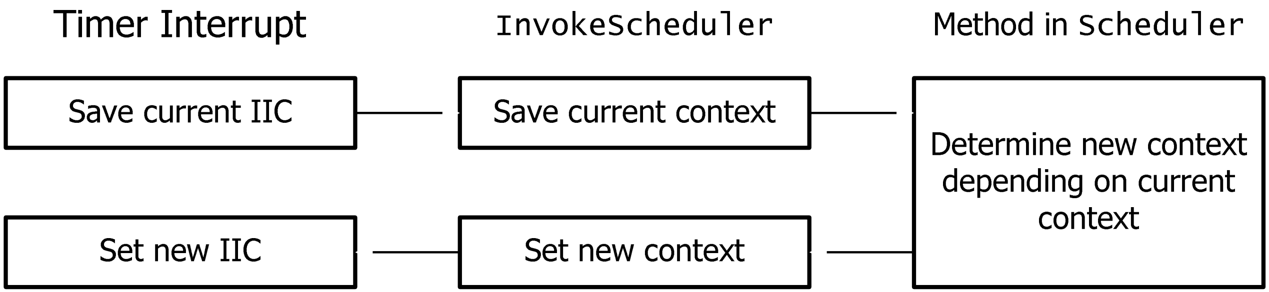
```
[InterruptHandler]
static void Handler ()
{
  /* any code */
}

public static void Main ()
{
  Hardware.VectorTable.NonMaskableInterrupt = Handler;
}
```

or in C# 1.0:

```
Hardware.VectorTable.NonMaskableInterrupt =
   new InterruptHandler (null, Handler);
```

Implementing Preemptive Concurrency

```
static void Main ()
{
   Cpu.Scheduler = DetermineNext;
   Hardware.VT.TimerInterruptVector = Cpu.InvokeScheduler;
   Timer.Start ();
   while (true) Cpu.Sleep ();
}

// Class Cpu is implemented target specific
public static Cpu.Context DetermineNext (Cpu.Context context)
{
   Cpu.Context newContext;
   /* determine the new context */
   return newContext;
}
```



Status and Ongoing Work

- Our gcc front-end supports interrupt handling and direct memory access as suggested
- Acceptable overhead (max. 50%) of generated code compared to „hand-written“ assembler
- Acceptable compilation times
- Supported target Platforms: H8-300 Lego Mindstorm RCX 2.0
- Current projects:
  - OS#: micro-kernel operating system using Real-Time.Net
  - Support for latest Lego NXT hardware (ARM)

Conclusions

- New extension for the standard ECMA 335
- General approach for mapping hardware registers to structured value types
- Enables OEMs to specify their hardware in high-level languages
- Attributed-based declaration of interrupt handler methods
- Approach for hardware-near programming using more productive high-level languages

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http://www.dcl.hpi.uni-potsdam.de

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