Modern Embedded Software

Overview of QP™ Real-Time Embedded Frameworks and QM™ Model-Based Design Tool

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Presentation Outline

• Why is RTE programming so hard and what can we do about it?

• QP™ real-time embedded frameworks (RTEFs)

• QM™ model-based design (MBD) and code generation tool
Why is real-time programming hard (1)?

#1: **Shared-state** concurrency

- Preemption in shared-state system
  - Race Conditions
    - Mutual Exclusion
  - Blocking
    - Starvation
    - Deadlock
    - Priority inversion
    - Missed deadlines
    - Architectural decay
    - More threads
    - Unresponsive threads
    - Architectural decay

#2: Synchronization by **blocking**

- Synchronization by blocking
What can we do about it?

Experienced developers came up with **best practices**:

- **Don't share** data or resources (e.g. peripherals) among threads
  → Keep data isolated and bound to threads (strict **encapsulation**)

- **Don't block** inside your code
  → Communicate among threads **asynchronously** via event objects

- Threads should spend their lifetime responding to **events** so their main line should consist of “message pump”
  → Encapsulated thread + “message pump” → **Active Object (Actor)**

(*) Herb Sutter “Prefer Using Active Objects Instead of Naked Threads”
Active Object (Actor) Design Pattern

- **Active Object** (Actor) is an event-driven, **strictly encapsulated** software object running in its **own thread** and communicating **asynchronously** by means of **events**.
  
  → Not a real novelty. The concept known from 1970s, adapted to real-time in 1990s (ROOM actor), and from there into the UML (active class).

- The UML specification further proposes the UML variant of **hierarchical state machines** (UML statecharts) with which to model the **behavior** of event-driven active objects (active classes).
  
  → This addresses the “spaghetti code” problem (more about it later)

(*) Lavender, R. Greg; Schmidt, Douglas C. "Active Object"
(*) Herb Sutter "Prefer Using Active Objects Instead of Naked Threads"
(*) OMG Unified Modeling Language TM (OMG UML) Superstructure, formal/2011-08-06
Active Object pattern with conventional RTOS

Organize threads as “message pumps”
→ Threads process one event at a time (Run-to-Completion, RTC)
→ Threads block only on empty queue and don't block anywhere else
→ Threads communicate asynchronously (without blocking) by posting events to each other's queues
A Better Way: Real-Time Embedded Framework

- Implement the Active Object design pattern as a **framework**
  → The best way to capture an **architecture** and make it **reusable**
  → Raises the **level of abstraction** (directly linked to productivity)
- **Inversion of control**
  → The main difference between a framework and a toolkit (e.g., RTOS)
  → The main way to **automate** and **enforce** the best practices (**safer** design)
  → The main way to hide the difficult aspects from application (**safer** design)
  → The main way to bring **conceptual integrity** to the application
  → The main way to bring **consistency** among applications (product lines)
Paradigm Shift: Sequential → Event-Driven

- No blocking
  → Most RTOS mechanisms!
- No sharing
  → Use events with parameters instead
- No sequential code

```c
/* this "Blinky" code no longer flies */
while (1) { /* RTOS task or "superloop" */
  BSP_ledOn();  /* turn the LED on */
  OS_delay(500); /* blocking!!! */
  BSP_ledOff(); /* turn the LED off */
  OS_delay(500); /* blocking!!! */
}
```
Why is event-driven programming hard (2)?

- Responding to events leads to “spaghetti code”
  - The response depends on both: the event type and the **internal state** of the system
  - State of the system (history) is represented *ad hoc* as multitude of flags and variables
  - Convoluted, deeply nested IF-THEN-ELSE-SWITCH logic based on complex expressions → **spaghetti code**
What can we do about it?

- Finite State Machines—the best known “spaghetti reducers”
  - “State” captures only the relevant aspects of the system's history
  - Natural fit for event-driven programming, where the code cannot block and must return to the event-loop after each event)
  - Context stored in a single state-variable instead of the whole call stack

```cpp
 ANY_KEY / send_lower_case_scan_code();
```
Paradigm Shift: Sequential → Event-Driven (2)

State Machines are not Flowcharts (!)

Statechart (event-driven)
→ represents all states of a system
→ driven by explicit events
→ processing happens on arcs (transitions)
→ no notion of “progression”

(a)

Statechart (event-driven)

Flowchart (sequential)
→ represents stages of processing in a system
→ gets from node to node upon completion
→ processing happens in nodes
→ progresses from start to finish

(b)

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Input-driven state machines are **NOT** driven by events:
→ combination of polling for events and state machine logic
→ often called from “superloops” (while(1) loops)
→ transitions have only **guard conditions**

Hierarchical State Machines

Traditional FSMs “explode” due to repetitions

State hierarchy eliminates repetitions → programming-by-difference
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QP™ Real-Time Embedded Frameworks

- Family of frameworks for deeply embedded real-time systems: QP/C, QP/C++, QP-nano
  - Combines Active Object pattern with Hierarchical State Machines, which beautifully complement each other
  - Many advanced features yet lightweight (smaller than RTOS kernel)
- Good fit for systems with **functional safety** requirements
  - Sound, component-based architecture safer than “naked” RTOS
  - Provides means of designing applications based on **state machines** and **documented** as UML state diagrams (recommended by safety standards)
  - **Traceable** implementation in MISRA-compliant C or C++
Who is using QP™?

QP™ has been licensed by companies large and small in diverse industries:
→ Consumer electronics
→ Medical devices
→ Defense
→ Industrial controls
→ Communication & IoT
→ Robotics
→ Semiconductor IP
→ … (see online)

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## QP™ Framework Family Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>QP/C</th>
<th>QP/C++</th>
<th>QP-nano</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code (ROM) / Data (RAM) footprint</td>
<td>4KB / 1KB</td>
<td>5KB / 1KB</td>
<td>2KB / 0.5KB</td>
</tr>
<tr>
<td>Maximum number of active objects</td>
<td>64</td>
<td>64</td>
<td>8</td>
</tr>
<tr>
<td>Hierarchical state machines</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Events with arbitrary parameters</td>
<td>✓</td>
<td>✓</td>
<td>32-bits</td>
</tr>
<tr>
<td>Event pools and automatic event recycling</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Direct event posting</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Publish-Subscribe</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Event deferral</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Number of time events per active object</td>
<td>unlimited</td>
<td>unlimited</td>
<td>1</td>
</tr>
<tr>
<td>Software tracing support (Q-SPY)</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Cooperative QV kernel</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Preemptive, non-blocking QK kernel</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Preemptive, blocking kernel (QXK)</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Portable to 3rd-party RTOS</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>
QP™ vs. RTOS Memory Footprint

QP frameworks fit into smaller RAM, because event-driven programming style uses much less stack space.
QP™ Sub-Components

Active Object

Active Object

Active Object

Active Object

BSP

QS software tracing

QEP hierarchical event processor

QF active object framework

QV cooperative kernel, or
QK preemptive non-blocking kernel, or
QXK preemptive blocking RTOS kernel

Target hardware

Application (Your code)

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QEP Hierarchical Event Processor

```c
QState Calc_on(Calc * const me, QEvt const *e) {
    QState status;
    switch (e->sig) {
    case Q_ENTRY_SIG: /* entry action */
        BSP_message("on-ENTRY");
        status = Q_HANDLED();
        break;
    case Q_EXIT_SIG: /* exit action */
        BSP_message("on-EXIT");
        status = Q_HANDLED();
        break;
    case Q_INIT_SIG: /* initial transition */
        BSP_message("on-INIT");
        status = Q_TRAN(&Calc_ready);
        break;
    case C_SIG: /* state transition */
        BSP_clear(); /* clear the display */
        status = Q_TRAN(&Calc_on);
        break;
    case OFF_SIG: /* state transition */
        status = Q_TRAN(&Calc_final);
        break;
    default:
        status = Q_SUPER(&QHsm_top); /* superstate */
        break;
    }
    return status;
}
```
QF Framework – “Software Bus”

Publish-subscribe “software bus”

Multicasting a published event

direct event posting

ISR_1()
ISR_2()
QF Framework – “Zero Copy” Event Delivery

- «active» ProducerA
- «active» ProducerB
- ISR

- EventPool1
  - event queue holding pointers to events
  - pointers to event instances
  - dynamic events

- EventPool2
  - static event (not from a pool)

- internal state machine
- active object
- internal thread

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QV™ Cooperative RT-Kernel

find highest-priority non-empty queue

"vanilla" scheduler

all queues empty (idle condition)

priority = n

priority = n-1

priority = 1

e = queue.get();

dispatch(e);

e = queue.get();

dispatch(e);

... e = queue.get();

... dispatch(e);

idle processing

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QK™ Preemptive, Non-Blocking RT-Kernel

• Preemptive priority-based kernel
• Meets all requirements of Rate Monotonic Analysis (RMA)
• Run-to-Completion Kernel
  → Cannot block in-line
  → Single stack operation (like ISRs)

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QXK™ Preemptive, Blocking RT-Kernel

- A “bridge” to legacy software & middleware in sequential paradigm → Sequential threads can coexist with event-driven AOs
- Tightly integrated with QP (reuse of event queues, time events, etc.)
- More efficient way to run QP apps than any 3rd-party RTOS.

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QS/Spy™ Software Tracing System

- You need to observe system live, not stopped in a debugger
QUTest™ Unit Testing Harness

Specifically designed for **TDD** of deeply embedded software

→ Separates CUT execution from checking the test assertions
→ Small, reusable test fixture in the **Target** (C or C++ code)
→ Driving the tests and checking correctness on the **Host**
→ Python and Tcl test scripting
→ Specifically suitable for **event-driven** systems (simplifies “mocking”)

[Diagram: Use case diagram showing interaction between Target and Host with QUTest Test Script]

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QSpyView™ Front-End

- Customizable (scripted) Front-End for **monitoring** and **control** of embedded Targets
  - Remote User Interface
  - Graphic display of Target status
  - Dynamic interaction with Target
  - Remote resetting the Target

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Design by Contract (DbC)

- The QP's error-handling policy is based on DbC
- Preconditions / Postconditions / Invariants / General Assertions
  - DbC built-into the framework
  - Designed to catch problems in the application
  - No way of ignoring errors (enforcement of rules)
  - Provides redundancy and self-monitoring for safety-critical applications
- Example QP policies enforced by DbC
  - Event delivery guarantee (event pools and queues can't overflow)
  - Arming / disarming / re-arming of time events
  - System initialization, starting active objects
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QM™ Model-Based Design Tool

• Modeling and code-generation tool for QP™ frameworks
  → Adds graphical state machine modeling to QP™
  → QP™ RTEFs provide an excellent target for automatic code generation
QM™ Design Philosophy

- “Low ceremony”, code centric tool (no PIM, PSM, action-languages,…)
  → Not appropriate if you need these features (80% of benefits for 20% of costs)
- Optimized for C and C++, (no complexity to support other languages)
- Optimized for QP™ (no complexity to support other frameworks)
- Forward-engineering only (no complexity at “round-trip engineering”)
- Capture logical design (packages, classes, state machines)
- Capture physical design (directories and files generated on disk)
- Minimize “fighting the tool” while drawing diagrams and generating code
- Capable of invoking external tools, such as compilers, flash-downloaders…
- Freeware
Logical Design (Packages/Classes/Statecharts)
Physical Design (Directories / Files)

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Extending QM™ with Command-Line Tools

Environment Variables:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAR_EWARM</td>
<td>C:\tools\IAR\ARM\KS_7.10</td>
</tr>
</tbody>
</table>

External Tools:

- IAR build-Debug
- PC-lint
- qspy
- qclean
- Imflash

Log Console:

```
INFO: Code generation started (07:21:17.862 am)
INFO: Entire model: D:\np\examples\arm-embed\ iar\game-qk.ek-1m3s81
INFO: Code generation ended (time elapsed 0.0315)
INFO: 0 file(s) generated, 7 file(s) processed, 0 error(s), and 0 warn
%IAR_EWARM\common\bin\IARBuild.exe game-qk -build Debug
IAR Command Line Build utility V7.0.3.3119
Copyright 2002-2014 IAR Systems AB.
Building configuration: game-qk - Debug
Updating build tree...
s3 file(s) deleted.
Updating build tree...
bsp.c
display9x16x1.c
main.c
mine1.c
mine2.c
missile.c
ship.c
startup_1m3s.c
system_1m3s.c
tunnel.c
Linking
game-qk.out
Total number of errors: 0
Total number of warnings: 0
}} External tool finished normally with status 0
```
Welcome to the 21st Century!

- Experts avoid shared-state concurrency and blocking
- Experts use the event-driven Active Object design pattern
- Experts use hierarchical state machines instead of “spaghetti code”
- Event-driven active objects and state machines require a paradigm shift from sequential to event-driven programming
- QP™ real-time embedded frameworks (RTEFs) provide a lightweight, reusable architecture based on the AO pattern and hierarchical state machines for deeply embedded systems, such as single-chip MCUs
- QM™ model-based design tool eliminates manual coding of HSMs

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