Towards a Resilient Operating System for Wireless Sensor Networks

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Motivation (1)

- **Problems: Application errors on sensor networks**

Diverse hardware devices

Cooperate with large number of nodes

Unattended operation for long-time

Kernel data corruption

Kernel code execution

Hardware control faults

Kernel fail & sensor node crash

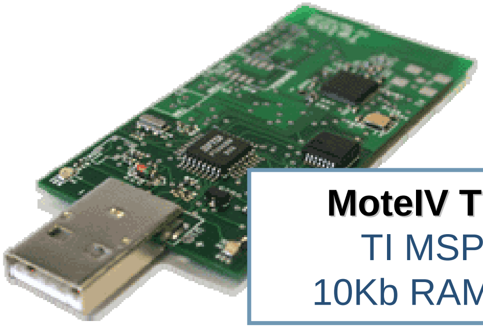
No way to recover from system failure

Crashed sensor node is useless in the field

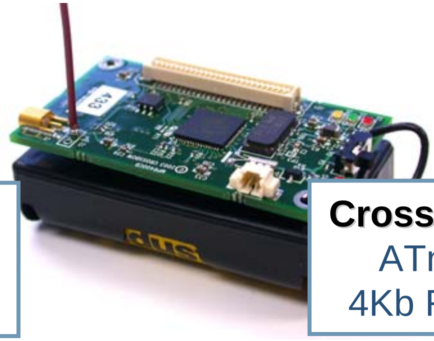
System safety like general purpose OS needed!

Motivation (2)

- **Popular sensor nodes: Telos / Mica**



MoteIV Telos Rev. B
TI MSP430 8Mhz
10Kb RAM, 60Kb ROM



CrossBow Mica2, MicaZ
ATmega128L 8Mhz
4Kb RAM, 128Kb ROM

  – No MMU, privileged mode, and exceptions

- **Current sensor network systems**

Sensor operating systems

TinyOS | SOS | MANTIS

Virtual machine

Maté

  – No system safety mechanism

Towards Resilient Sensor Networks

- **Ensure system safety at the operating system level**
  - **Applications** : we cannot write the code safely all the time
  - **Sensor node hardware** : does not easily detect application errors

- **Objectives**
  - Provide error-safe mechanism on resource-constrained sensor devices
  - Do not require any hardware supports
  - Do not require users to learn new programming language semantics

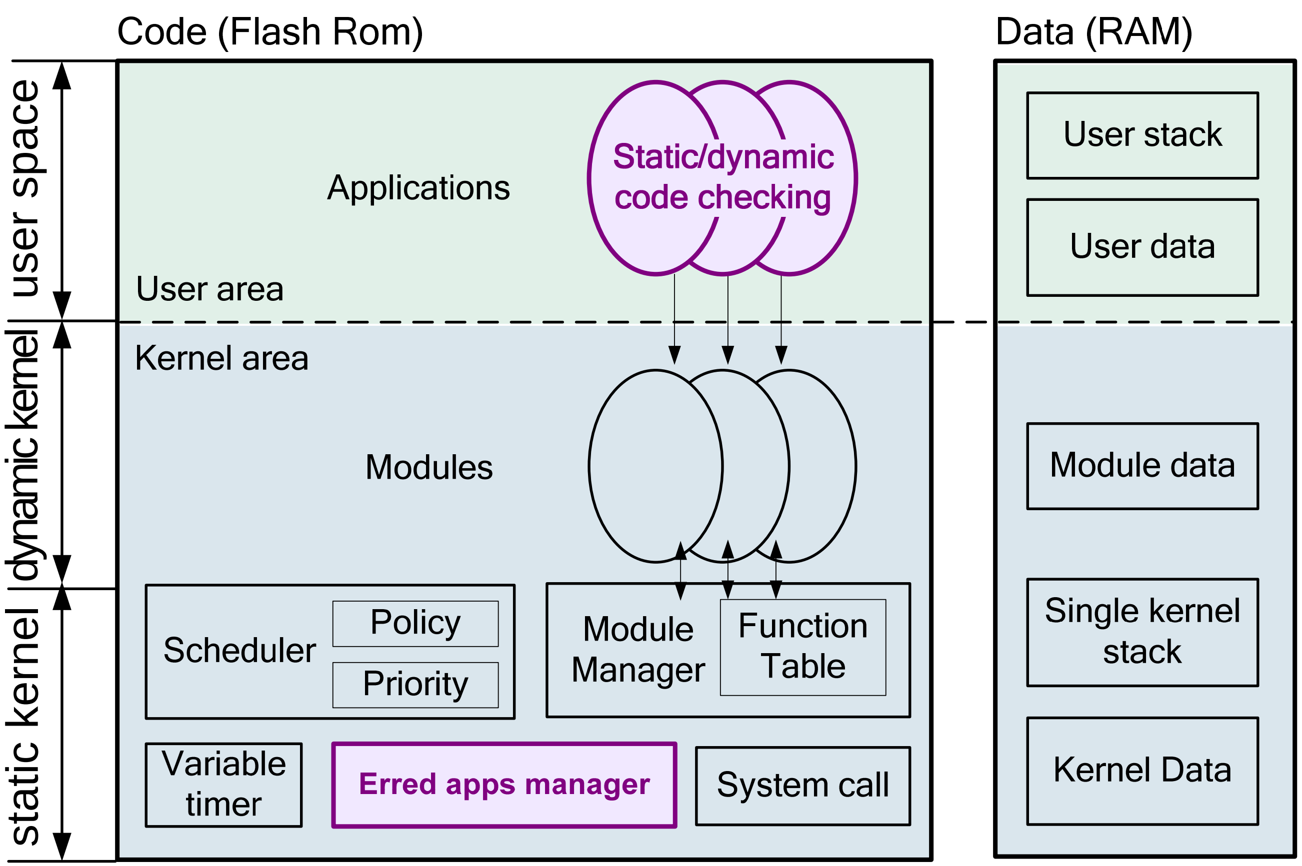
Previous Work

- **SFI (Software Fault Isolation)**
  - Requires MMU for segmentation and stack safety
  - Designed for fixed-length instruction architecture
- **Proof-carrying Code**
  - The automatic policy generator does not exist
- **Programming language approaches**
  - Cyclone, Control-C, Cuckoo
  - Users should be aware of the different usages of pointer/array
  - Requires hardware supports for stack safety

- T. Jim, G. Morrisett, D. Grossman, M. Hicks, J. Cheney, and Y. Wang, **"Cyclone: A safe dialect of C,"** *Proc. of the 2002 USENIX Annual Technical Conference,* June 2002.
- D. Dhurjati, S. Kowshik, V. Adve, and C. Lattner. **"Memory safety without runtime checks or garbage collection,"** *Proc. of Languages, Compilers and Tools for Embedded Systems*, 2003.
- R. West, and G. T. Wong, **"Cuckoo: a Language for Implementing Memory and Thread-safe System Service"**, Proc. of International Conference on Programming Languages and Compilers, 2005.

RETOS Architecture

Resilient, Expandable, and Threaded Operating System



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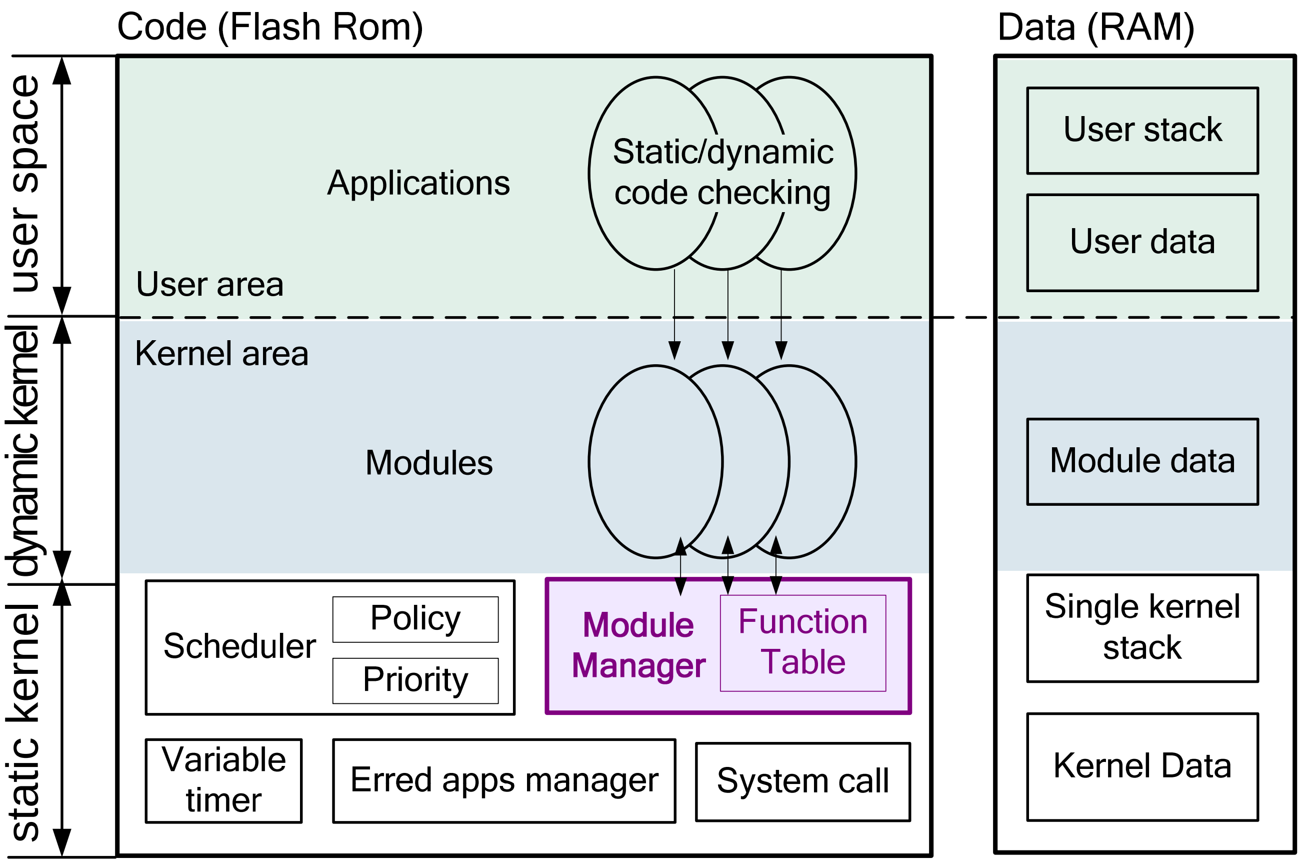

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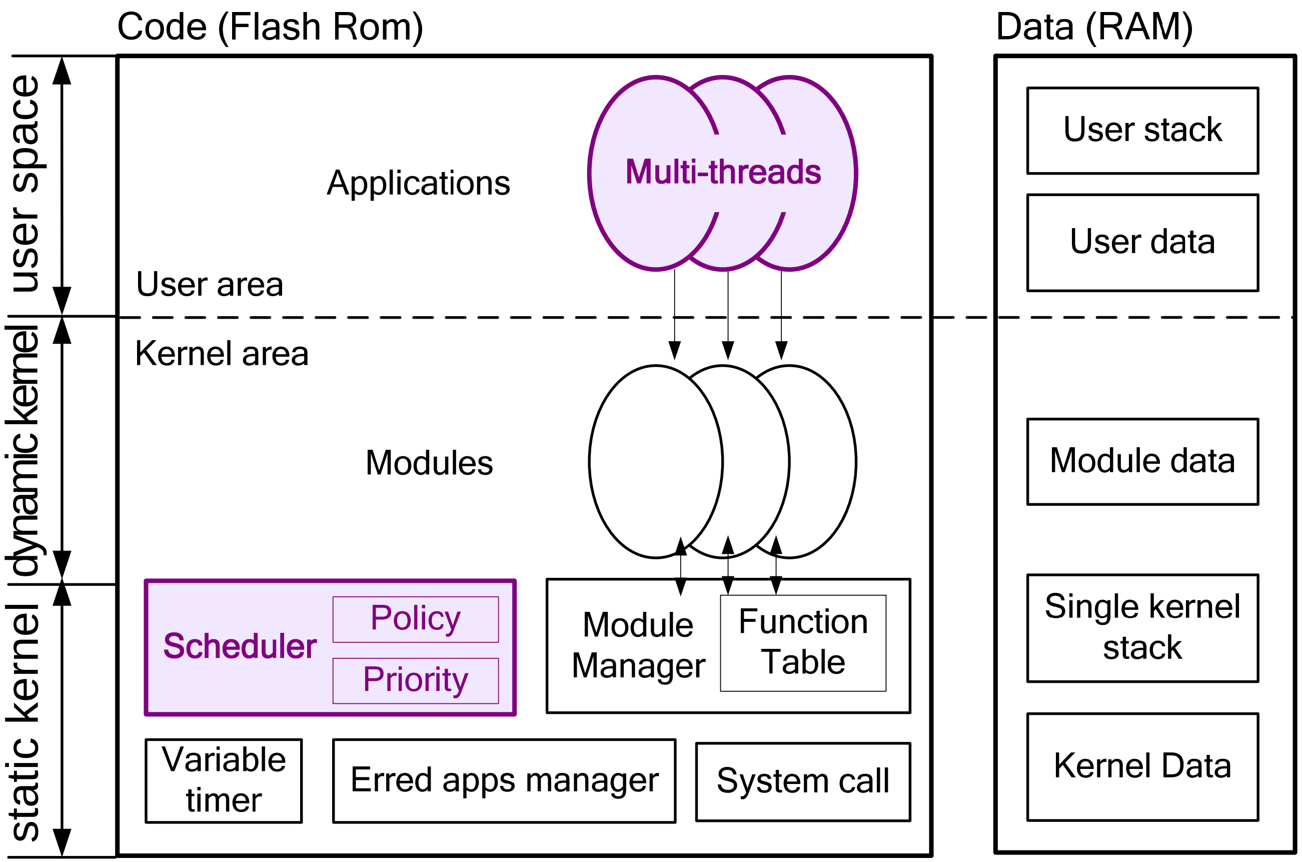
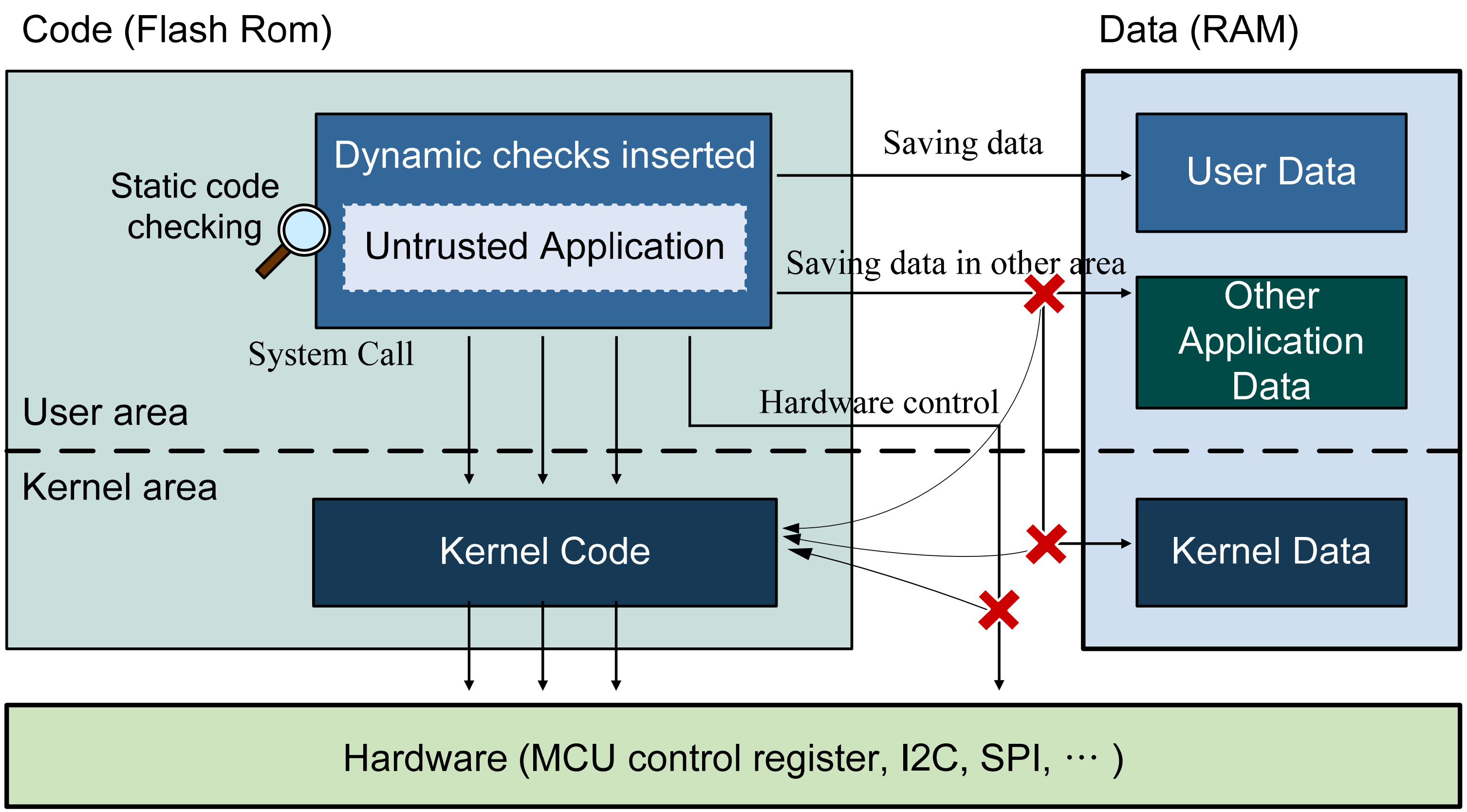
Resilient, Expandable, and Threaded Operating System



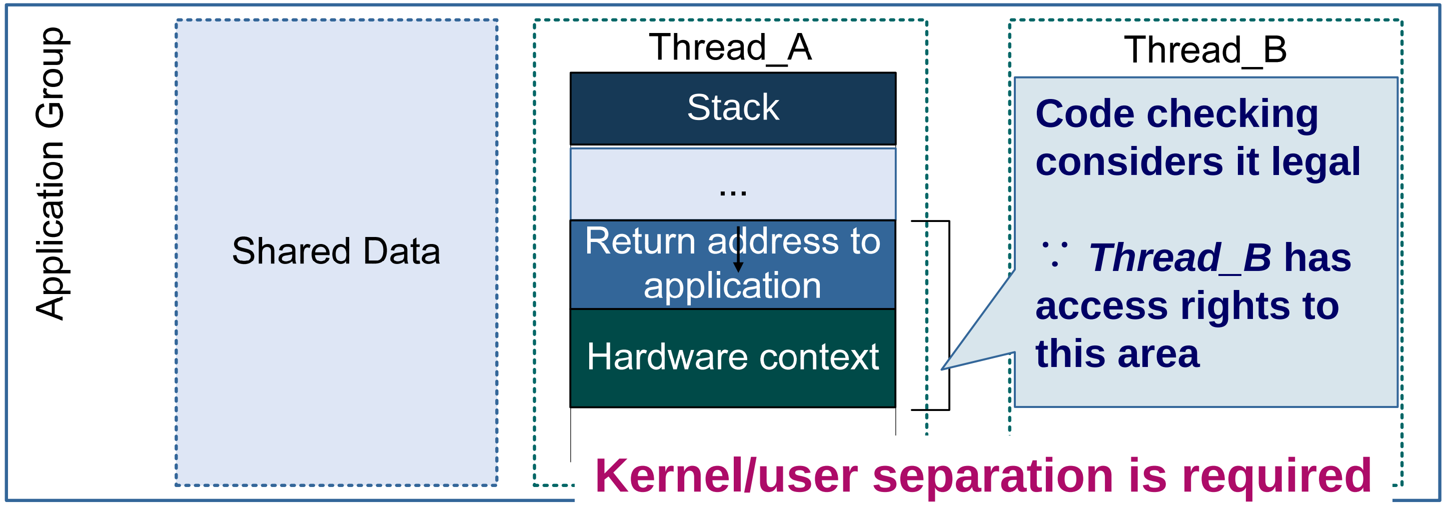
Ensuring System Safety

- **Principle**
  - Dual Mode operation & static/dynamic code checking



Dual Mode Operation

- **Why dual-mode is needed?**
  - Static/dynamic code checking evaluates if the application modifies data or issues code in its allocated data
  - Preemption would invoke problems
- **(ex) *Thread_A* is preempted by *Thread_B***



Static/Dynamic Code Checking

- Use data and code area within application itself
- Restrict direct hardware resource manipulation

Application Source Code → Assembly Code → Dynamic Checks Insertion → Binary Code → Static Code Checking → Trusted Application Code

```c
#include <io.h>
#include <syscall.h>
#include <pthread.h>

...

/* main thread */
int main ()
{
    while (1) {
        void (*func)(void);
        /* radio packet recv */
        radio_recv(PORT, &pkt);
        func = foo_func[pkt->id];

        /* do something*/

        func();
    }
}
```

Application Source Code

```
main:
/* prologue: frame size = 44 */
.L__FrameSize_main=0x2c
.L__FrameOffset_main=0x2e
        mov     #(__stack-44), r1
/* prologue end (size=2) */
.L23:
/* do something */
        call    &func
        mov     #llo(6), r15
        call    #_syscall0
        jmp     .L5
        br      #__stop_progExec__
/* epilogue: frame size=44 */
        add     #44, r1
        br      #__stop_progExec__
/* epilogue end (size=4) */
/* function main size 168 (162) */
.Lfe6:
        .size   main,.Lfe6-main
```

Dynamic Checks Insertion

Static Code Checking

```
mov     #1792,   r1
mov     #6,      r15
push    r15
mov     &0x0608,r15
cmp     12(r15),r1
jnc     $+8
cmp     14(r15),r1
jnc     $+6
call    #4488
pop     r15
call    #4494
mov     #1000,   r13
clr     r14
mov     #40,     r15
push    r15
mov     &0x0608,r15
cmp     12(r15),r1
jnc     $+8
cmp     14(r15),r1
jnc     $+6
call    #4488
```

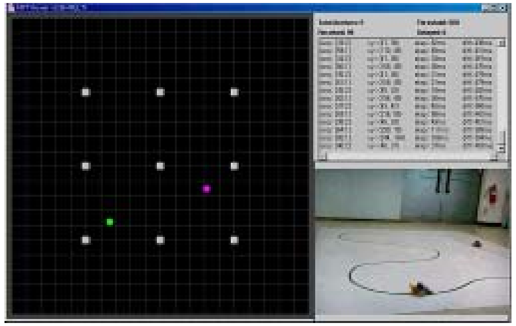
Trusted Application Code

Implementation

- **RETOS implemented on TI MSP430 F1611**
  - 8MHz core clock, 10Kb RAM, 48Kb Flash ROM
  - Current version: 0.92 (May 24 2006)

- **Peripheral supports**
  - 2.4Ghz RF Module (Chipcon 2420)
  - Ultrasound, Humidity, and Light sensors

- **Applications: MPT (Multi-Party Object Tracking)**



Functionality Test (1)

- **Classify safety domain into four parts:**
  - Stack / Data safety → Stack and data area
  - Code safety → Control flow
  - Hardware safety → Immediate hardware control

Hardware safety

Disable interrupt

```
DINT();
```

→ Detected by **Static check**

Flash ROM writing
(memory mapped registers)

```
FCTL1 = FWKEY+WRT;
```

→ Detected by **Static check**

Stack safety

General/Mutual recursive call

```
void foo() {
        foo();
}
```

```
void foo() {            void bar() {
        bar();                  foo();
}                       }
```

→ Detected by **Dynamic check**

Functionality Test (2)

Data safety

Directly addressed pointers

```
int *tmp = 0x400;
*tmp = 1;
```

→ Detected by **Static check**

Illegal array indexing

```
/* array in heap area */
int array[10];
…
for(i = 10; i > 0; i--) {
        array[i-100] = i;
}
```

→ Detected by **Dynamic check**

Code safety

Directly addressed function call

```
void (*func)(void) = 0x1000;
func();
```

→ Detected by **Static check**

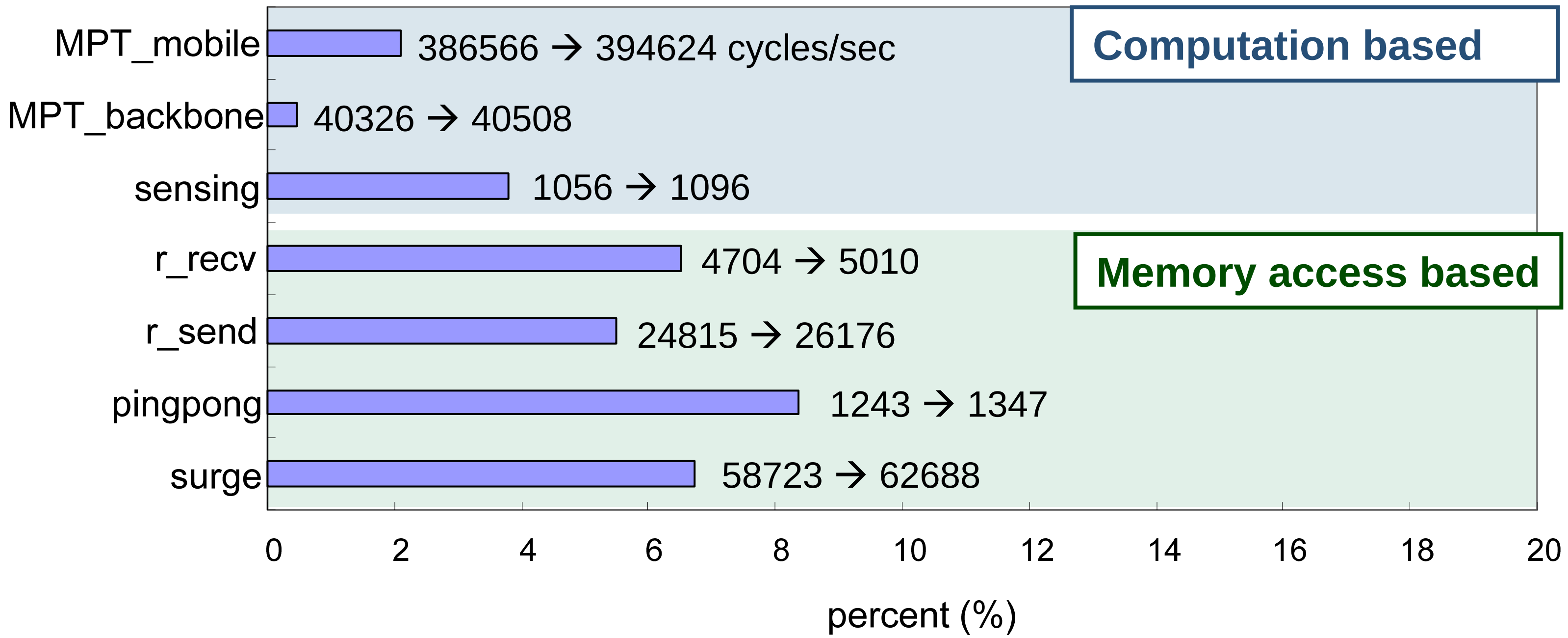
Corrupted return address (Buffer overflow)

```
void func() {
        int array[5], i;
        for(i = 0; i < 10; i++)
                array[i] = 0;
}
```

→ Detected by **Dynamic check**

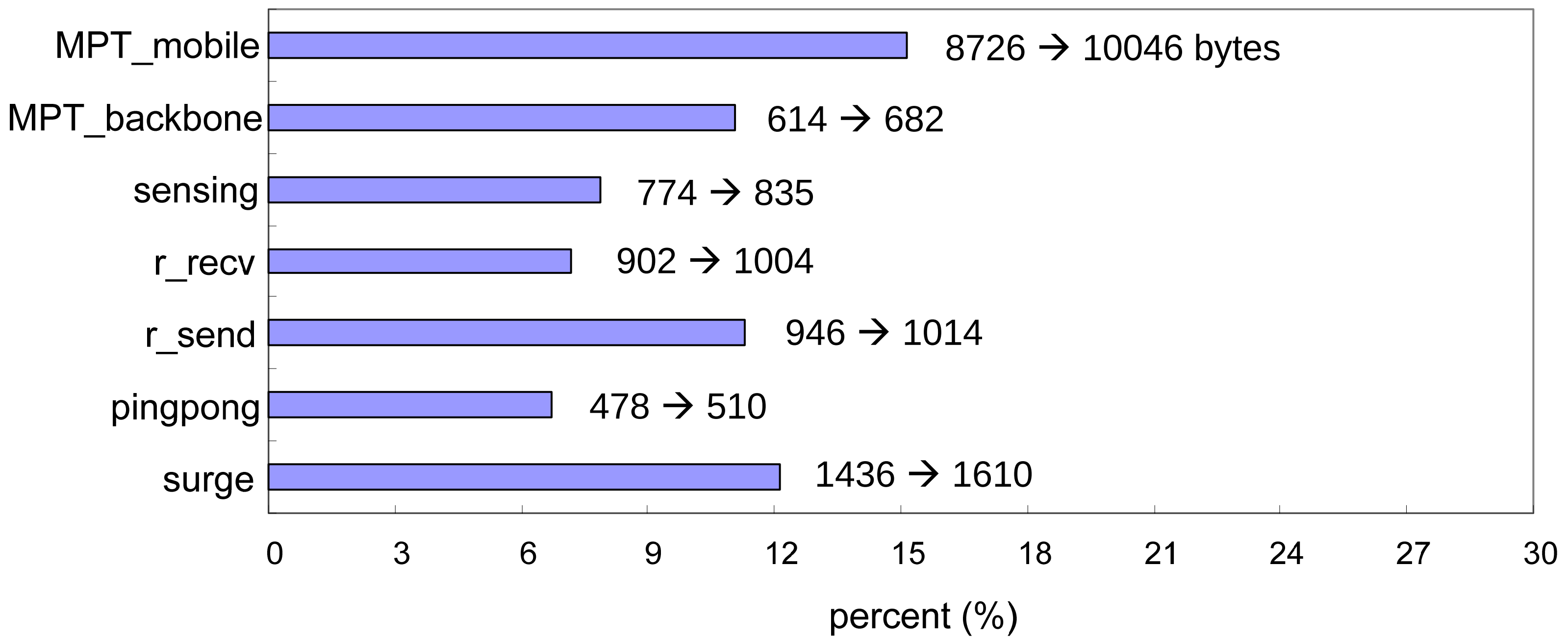
Overhead Analysis (1)

- **Execution time running in user mode**
  - Programs, which require more memory access than complex arithmetic calculations, shows larger overhead



Overhead Analysis (2)

- **Application code size comparison**
  - Code size increased, independent of application type
  - Applications are inherently small in size, separated from kernel



Overhead Analysis (3)

- **Dual mode operation**

	Single mode (cycles)	Dual mode (cycles)	**Overhead (cycles)**
system call (led toggle)	264	302	**38**
system call (radio packet send)	352	384	**32**
timer interrupt (invoked in kernel)	728	728	**0**
timer interrupt (invoked in user)	728	760	**32**

- **Summary**
  - Computational overhead & larger code size are inevitable to provide system safety in sensor node platform
  - However, they are considered as a fair trade-off compared to a system failure

Conclusions

- **Safety mechanism for wireless sensor networks**
  - Separate errant application from the kernel, “Kernel never die”
  - Automatically recover from serious errors
  - Useful in the real, large-scale sensor networks

- **Current status**
  - RETOS is being developed in our research group
  - Being ported to other processors (AVR)
  - “Application-Centric Networking Framework for Wireless Sensor Networks”
    - *Mobiquitous 2006,* San Jose, July 17-21

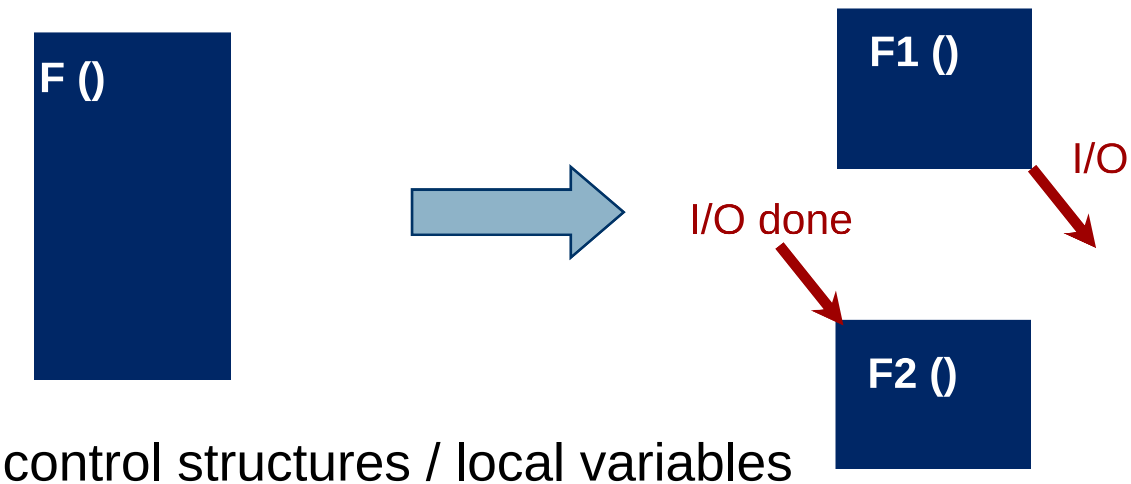
Questions

WatchdogTimer

- **Not easy to recognize and handle problems such as:**
  - Memory access beyond the application area
  - Immediate hardware control
- **Watchdog timer simply makes the system be restarted**
  - One errant application can stop all other applications
  - Disturbance of long-term operations of sensor applications

Multithread vs. Event-driven

- **Concurrency for computation based applications**
  – **Run-to-completion** vs. **preemptive time-sliced thread**
- **Poor software structure on event-driven model**
  – One conceptual function split into multiple functions



  – Loss of control structures / local variables
- **Simplified synchronization methods on thread model**
  – Like “atomic” operation in nesC

Limitations

- **Library codes**
  - We assume the libraries always operate safely
  - In real situation: If a user passes an invalid address to *memcpy()*?
  - Make wrapper functions that checks address parameters
- **Divide by zero**
  - Hardware multiplier/divider equipped processor
    : instruction level checking
  - Emulated : library level checking
- **Intentionally skips the code checking sequences**
  - User authentication on code updating would be required

Sensor OS Comparison

	System Safety (kernel-user separation)	Light-weight dynamic reprogramming	Programming Model	Programming Language
TinyOS	**No**	**No**	**Event-driven**	**nesC**
SOS	**No**	**Yes**	**Event-driven**	**Standard C**
MANTIS	**No**	**No**	**Preemptive Multithreading**	**Standard C**
RETOS	**Yes**	**Yes**	**Preemptive Multithreading**	**Standard C**