University of Glasgow | School of Computing Science

Real-time & Embedded Systems Programming

Advanced Operating Systems
Lecture 7

Lecture Outline

- Ensuring predictable timing
- Embedded systems
  - Constraints
  - Interacting with hardware
  - Device drivers
- Correctness and system longevity
- Low-level programming environments
  - Current and alternative approaches

Ensuring Predictable Timing

- Scheduling theory gives proof of correctness – if timing of system well understood
- Numerous sources of unpredictability
  - Timing variation due to dependence on algorithm input values → measure
  - Blocking due to resource access
  - Preemption by higher priority tasks or interrupt handlers
  - Processor cache improves average timing, with poor worst-case bounds
  - Virtual memory – address translation, paging, memory protection
  - Memory allocation and management – `malloc()` or garbage collector
- Avoid by defensive programming
  - Disable or avoid features that cause timing variation
  - Optimise for predictability, not raw performance

Embedded Systems

- Constraints on embedded systems:
  - Must interact with hardware to manipulate their environment – custom device drivers and low-level hardware access in application code
  - Safety critical or simply hard to upgrade – strong correctness constraints
  - Often resource constrained, with a low-level programming model
- Issues differ from those inherent in traditional desktop application programming

Interacting with Hardware

- Devices represented by bit fields at known address
  - Bit-level manipulation needed to access fields in control register
  - Code needs memory address and size of control register, layout, endianness, and meaning of bit fields within the register
- C allows definition of bit fields and explicit access to particular memory addresses via pointers – needed for implementation of device drivers
- Illusion of portability – standard C does not specify:
  - Size of basic types (e.g., a `char` is *not* required to be 8 bits, an `int` is *not* required to be 32 bits, etc.)
  - Bit and byte ordering
  - Alignment or atomicity of memory access
  - Each compiler/operating system defines these for its environment; the `<stdint.h>` and `<limits.h>` headers provide definitions to help with portability, but with weak type checking
- Device drivers written in C a frequent source of bugs
- Other languages (e.g., Ada) provide strict definitions and allow for stronger type checking

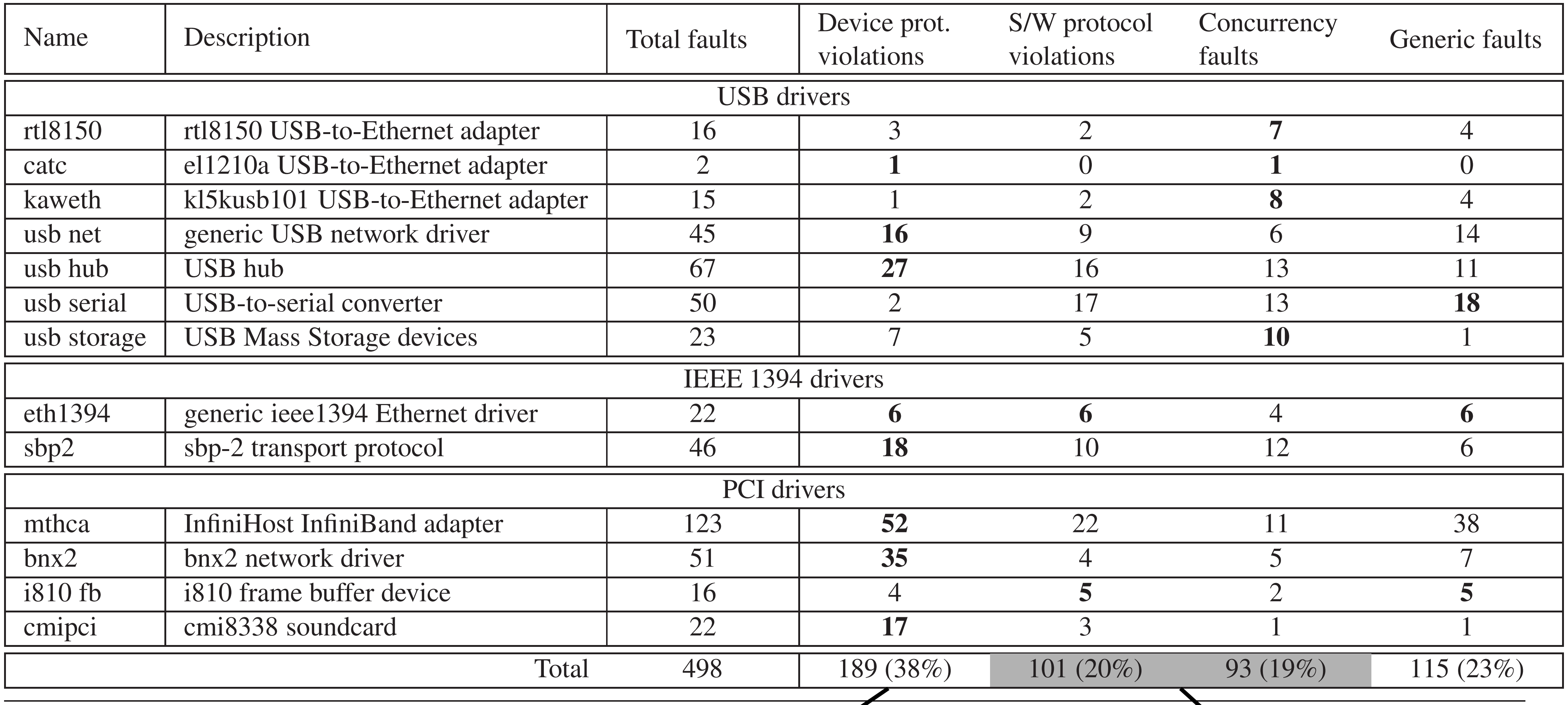
```
struct {
    short errors     : 4;
    short busy       : 1;
    short unit_sel   : 3
    short done       : 1;
    short irq_enable : 1
    short reserved   : 3
    short dev_func   : 2;
    short dev_enable : 1;
} ctrl_reg;

int enable_irq(void)
{
    ctrl_reg *r = 0x80000024;
    ctrl_reg  tmp;

    tmp = *r;
    if (tmp.busy == 0) {
        tmp.irq_enable = 1;
        *r = tmp;
        return 1;
    }
    return 0;
}
```

Example: hardware access in C

Sources of Bugs in Device Drivers (1)



Name	Description	Total faults	Device prot. violations	S/W protocol violations	Concurrency faults	Generic faults
			USB drivers			
rtl8150	rtl8150 USB-to-Ethernet adapter	16	3	2	**7**	4
catc	el1210a USB-to-Ethernet adapter	2	**1**	0	**1**	0
kaweth	kl5kusb101 USB-to-Ethernet adapter	15	1	2	**8**	4
usb net	generic USB network driver	45	**16**	9	6	14
usb hub	USB hub	67	**27**	16	13	11
usb serial	USB-to-serial converter	50	2	17	13	**18**
usb storage	USB Mass Storage devices	23	7	5	**10**	1
			IEEE 1394 drivers			
eth1394	generic ieee1394 Ethernet driver	22	**6**	**6**	4	**6**
sbp2	sbp-2 transport protocol	46	**18**	10	12	6
			PCI drivers			
mthca	InfiniHost InfiniBand adapter	123	**52**	22	11	38
bnx2	bnx2 network driver	51	**35**	4	5	7
i810 fb	i810 frame buffer device	16	4	**5**	2	**5**
cmipci	cmi8338 soundcard	22	**17**	3	1	1
	Total	498	189 (38%)	101 (20%)	93 (19%)	115 (23%)

Fix through device documentation and better language support for low-level programming?

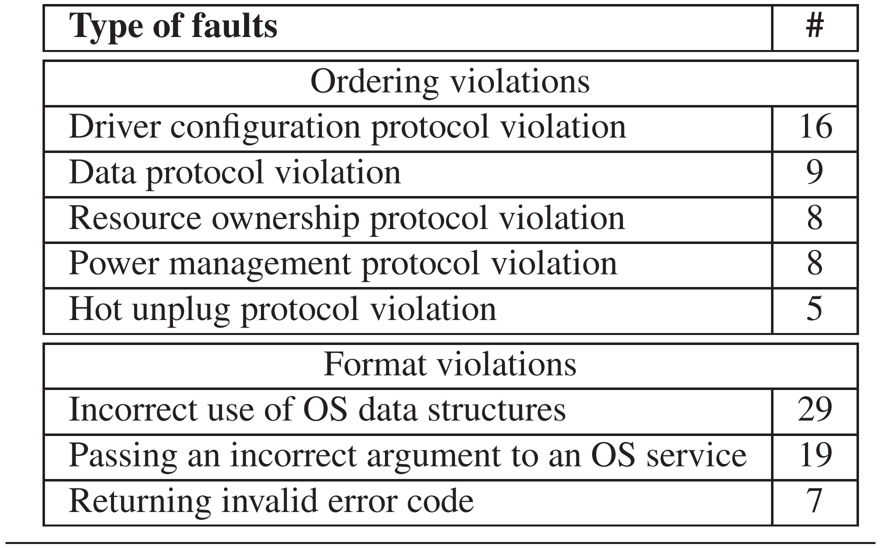
Can we address these through improvements to the supporting infrastructure for device-drivers?

Summary cause of bugs found in Linux USB, Firewire (IEEE 1394), and PCI drivers from 2002–2008
[from L. Ryzhyk *et al.*, “Dingo: Taming device drivers”, Proc. EuroSys 2009, DOI 10.1145/1519065.1519095]

Device protocol violations are mis-programming of the hardware, software protocol violations and concurrency faults are invalid interactions with the rest of the Linux kernel

Sources of Bugs in Device Drivers (2)

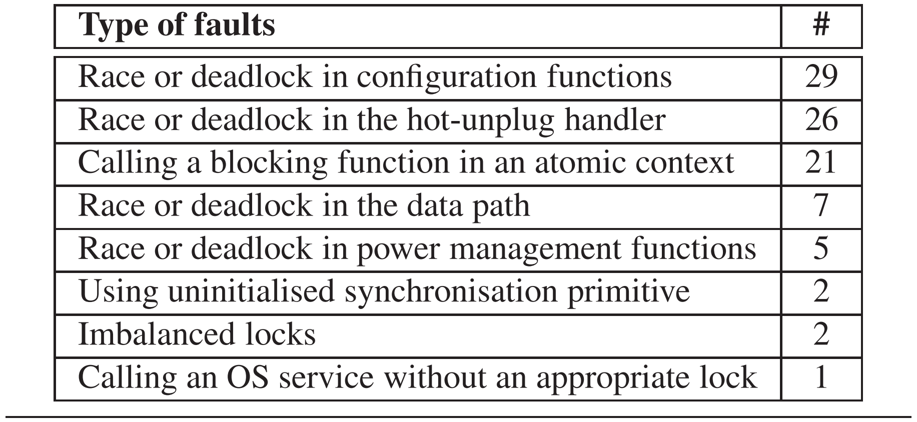
- What causes software protocol violations and concurrency faults?
  - Misunderstanding or misuse of the kernel device driver API functions, especially in uncommon code paths (e.g., error handling, hot-plug, power management)
  - Incorrect use of locks leading to race conditions and deadlocks



Type of faults	#
Ordering violations	
Driver configuration protocol violation	16
Data protocol violation	9
Resource ownership protocol violation	8
Power management protocol violation	8
Hot unplug protocol violation	5
Format violations	
Incorrect use of OS data structures	29
Passing an incorrect argument to an OS service	19
Returning invalid error code	7

Table 2. Types of software protocol violations.

- Bad programming and poor documentation of kernel APIs and locking requirements?
- Or error-prone programming languages, concurrency models, and badly designed kernel APIs?



Type of faults	#
Race or deadlock in configuration functions	29
Race or deadlock in the hot-unplug handler	26
Calling a blocking function in an atomic context	21
Race or deadlock in the data path	7
Race or deadlock in power management functions	5
Using uninitialised synchronisation primitive	2
Imbalanced locks	2
Calling an OS service without an appropriate lock	1

Table 3. Types of concurrency faults.

[from L. Ryzhyk *et al*., “Dingo: Taming device drivers”,
Proc. EuroSys 2009, DOI 10.1145/1519065.1519095]

Improving Device Drivers – Engineering

- Model device drivers in object-oriented manner
  - Device drivers generally fit some hierarchy
  - Use object-oriented language; encode common logic into a superclass, instantiated by device-specific subclasses that encode hardware details
    - May be able to encode protocol state machines in the superclass, and leave the details of the hardware access to subclasses (e.g., for Ethernet or USB drivers)
    - May be able to abstract some of the details of the locking, if the hardware is similar enough
  - Might require multiple inheritance or mixins to encode all the details of the hardware, especially for multi-function devices
- Implementation choices – device driver framework
  - Linux kernel implements this model in C, with much boilerplate
  - MacOS X uses restricted subset of C++ within kernel – simplifies driver development by encoding high-level semantics within framework, leaves only device-specific details to individual drivers

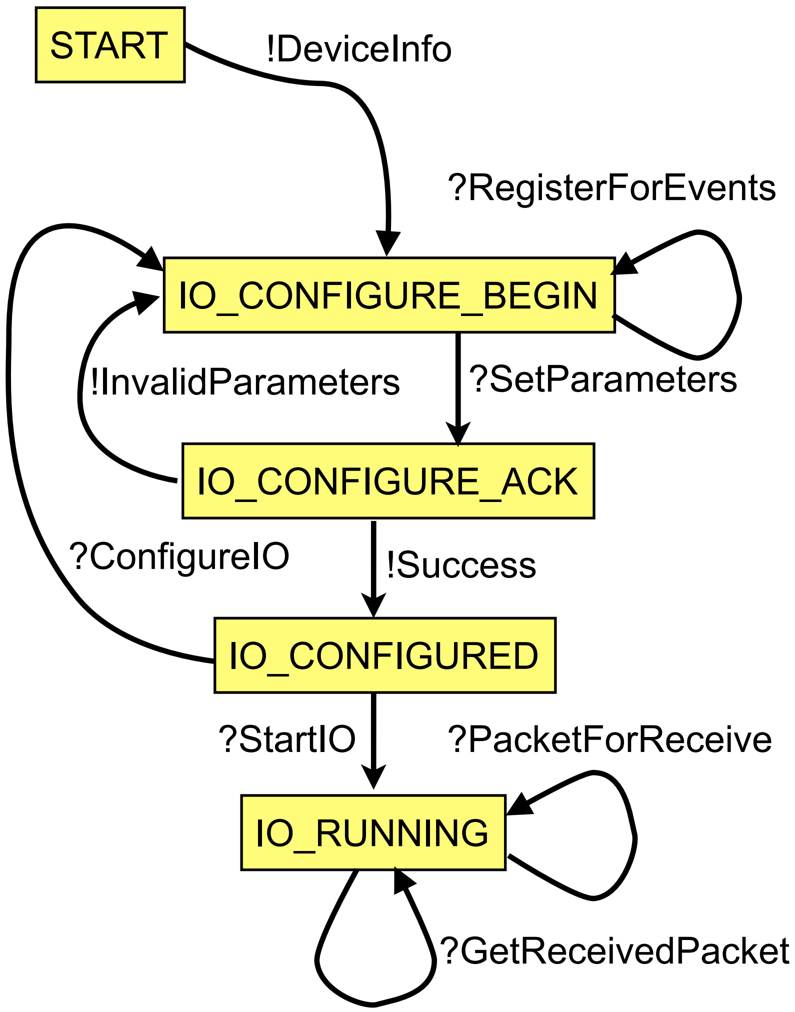
Apple, Inc. "I/O Kit Fundamentals", 2007
http://developer.apple.com/library/mac/documentation/DeviceDrivers/Conceptual/IOKitFundamentals/IOKitFundamentals.pdf

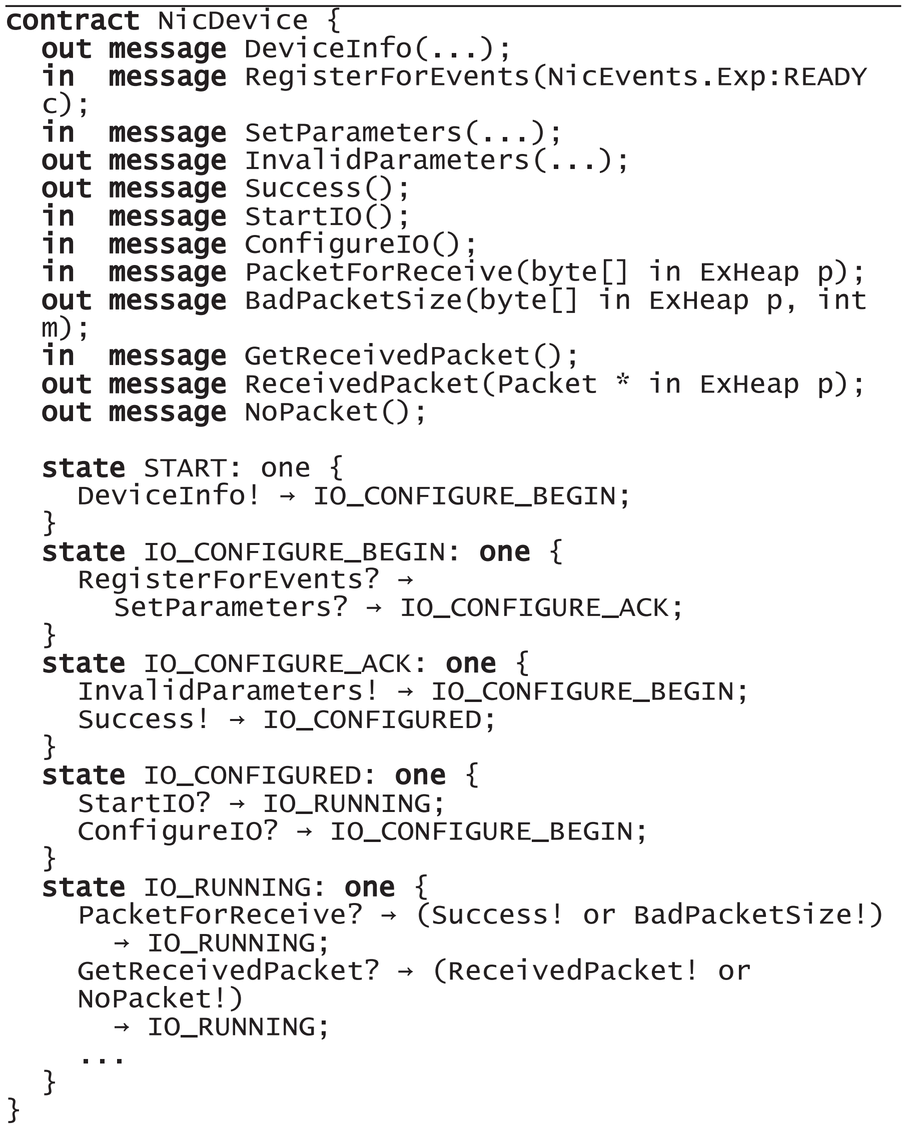
Improving Device Drivers – State Models

- An ad-hoc device driver model is common
  - Many bugs due to poor specification and documentation of the model
  - Use of object-oriented languages can improve this somewhat, but need careful integration into C-based kernels
- Possible to formalise design as a state machine
  - Make underlying state machine visible in the implementation – MacOS X I/O Kit models incoming events, but not the states, allowable transitions, or generated events
  - Could formally define full state machine in source code, allow automatic verification that driver implements the state machine for its device class, and model checking of the state machine
    - Can be implemented within existing languages, by annotating the code
    - Fits better with more sophisticated, strongly-typed, languages, that can directly model system

Improving Device Drivers – State Models

Example: the Singularity operating system from Microsoft Research





```
contract NicDevice {
  out message DeviceInfo(...);
  in  message RegisterForEvents(NicEvents.Exp:READY
  c);
  in  message SetParameters(...);
  out message InvalidParameters(...);
  out message Success();
  in  message StartIO();
  in  message ConfigureIO();
  in  message PacketForReceive(byte[] in ExHeap p);
  out message BadPacketSize(byte[] in ExHeap p, int
  m);
  in  message GetReceivedPacket();
  out message ReceivedPacket(Packet * in ExHeap p);
  out message NoPacket();

  state START: one {
    DeviceInfo! → IO_CONFIGURE_BEGIN;
  }
  state IO_CONFIGURE_BEGIN: one {
    RegisterForEvents? →
      SetParameters? → IO_CONFIGURE_ACK;
  }
  state IO_CONFIGURE_ACK: one {
    InvalidParameters! → IO_CONFIGURE_BEGIN;
    Success! → IO_CONFIGURED;
  }
  state IO_CONFIGURED: one {
    StartIO? → IO_RUNNING;
    ConfigureIO? → IO_CONFIGURE_BEGIN;
  }
  state IO_RUNNING: one {
    PacketForReceive? → (Success! or BadPacketSize!)
      → IO_RUNNING;
    GetReceivedPacket? → (ReceivedPacket! or
    NoPacket!)
      → IO_RUNNING;
    ...
  }
}
```

Listing 1. Contract to access a network device driver.

G. Hunt and J. Larus. "Singularity: Rethinking the software stack", ACM SIGOPS OS Review, 41(2), April 2007. DOI:10.1145/1243418.1243424

Improving Device Drivers – Discussion

- Focus on low-level implementation techniques and high-performance in many device driver models
- Not necessarily appropriate in embedded systems?

- Raising level of abstraction can reduce error-prone boilerplate, allow compiler to diagnose problems

Correctness and System Longevity

- Systems may be safety critical or difficult to update
  - Medical devices, automotive or flight control, industrial machinery
  - DVD player, washing machine, microwave oven, car engine controller
- Might need to run for many years, in environments where failures either cause injury or are expensive to fix
  - Can you guarantee your system will run for 10 years without crashing?
  - Do you check all the return codes and handle all errors?
  - Fail gracefully?

Low-level Programming Environment

- Embedded systems often constrained hardware
  - May have limits on power consumption (e.g., battery powered)
  - May have to be physically small and/or robust
  - May have strict heat production limits
  - May have strict cost constraints
- Used to throwing hardware at a problem, writing inefficient – but easy to implement – software
  - Software engineering based around programmer productivity
  - Constraints differ in embedded systems – optimise for correctness, cost, then programmer productivity

Development and Debugging

- Systems may be too limited to run compiler
    - Develop using a cross compiler running on a PC, download code using a serial line, or by burning a flash ROM and installing

- May have limited debugging facilities:
    - Serial line connection to host PC
    - LEDs on the development board
    - Logic analyser or other hardware test equipment
    - Formal proofs of correctness become more attractive when real system so difficult to analyse…

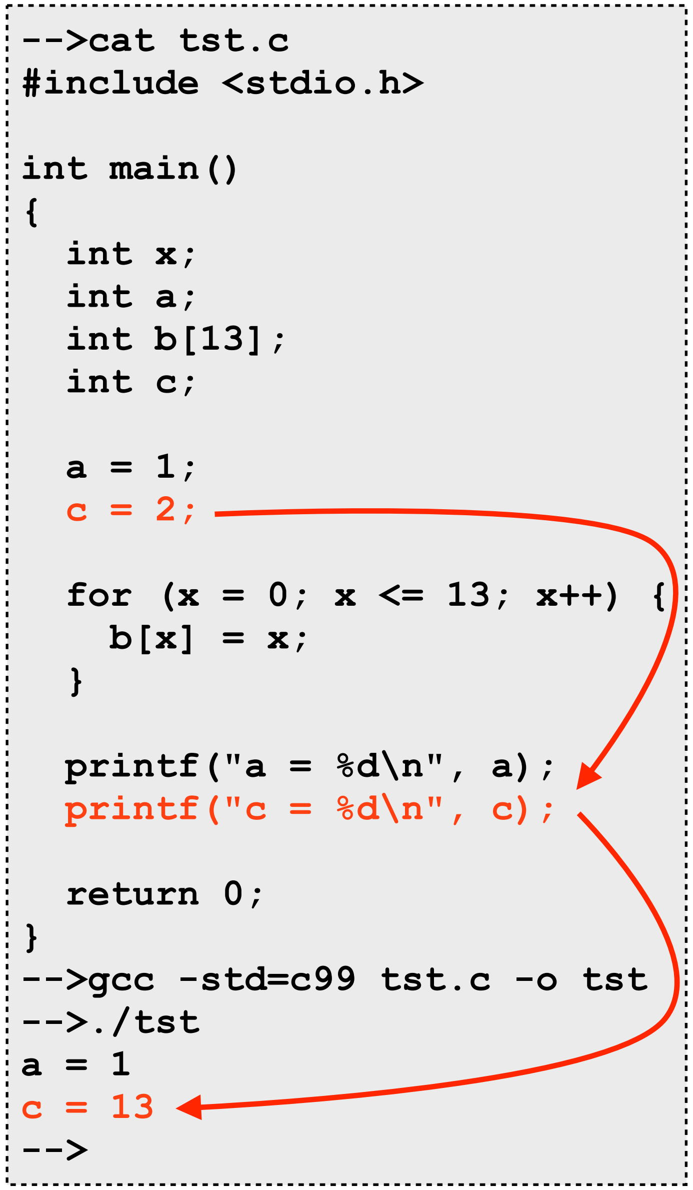
Alternative Programming Models

- Move away from C as an implementation language
    - Lack of type- and memory-safety leads to numerous bugs and security vulnerabilities
    - Limited support for concurrency – race conditions, locking problems – makes it unsuitable for modern machine architectures

- Move towards architectures with a minimal kernel, and strong isolation between other components of the operating system
    - The monolithic part of a kernel is a single failure domain; this needs to be reduced to a minimum → microkernel architecture
    - Easier to debug and manage components when they're isolated from each other, and communicate only through well-defined channels

Type- and Memory-Safe Languages

- Type safe language → protects its abstractions
  - Undefined behaviour prohibited by compiler/type system
  - The language specification can require that array bounds are respected, specify the error response to violation, etc.
  - More sophisticated type systems can catch more complex errors – e.g., enforce a socket is connected, check that an input string is correctly escaped to avoid SQL injection on web forms…
- Requires both compile- and run-time checking
  - The *type system* specifies legal properties of the program “for proving the absence of certain program behaviours”
  - Some properties can be statically checked by a compiler: a faulty program will not compile until the bug is fixed
  - Some properties require run-time checks: failure causes a controlled error
  - Doesn’t guarantee system works correctly, but ensures it fails in a predictable and consistent way
- Doesn’t require byte-code virtual machine; can have efficient implementation



```
-->cat tst.c
#include <stdio.h>

int main()
{
  int x;
  int a;
  int b[13];
  int c;

  a = 1;
  c = 2;

  for (x = 0; x <= 13; x++) {
    b[x] = x;
  }

  printf("a = %d\n", a);
  printf("c = %d\n", c);

  return 0;
}
-->gcc -std=c99 tst.c -o tst
-->./tst
a = 1
c = 13
-->
```

Modularity and Microkernels

- Desirable to separate components of a system, so failure of a component doesn’t cause failure of the entire system
- Microkernel operating system
    - Strip-down monolithic kernel to essential services; run everything else in user space communicating via *message passing* API
        - This includes devices drivers, network stack, etc.
        - Kernel just managing process scheduling, isolation, and message passing
    - Widely used in embedded systems, where robustness and flexibility to run devices for unusual hardware are essential features
    - But typically poor performance: frequent context switches expensive, due to need to cross kernel-user space boundary, manage memory protection, etc.

Strongly Isolated Systems

- A possible solution:
  - Microkernel that enforces all code written in a safe language (e.g., by only executing byte code, no native code)
    - This includes device drivers and system services running outside the microkernel
  - Type system prevents malicious code obtaining extra permissions by manipulating memory it doesn’t own – done entirely in software; no need to use MMU to enforce process separation
  - A *software isolated* message passing process architecture – loosely coupled and well suited to multicore hardware
  - Example: the Singularity operating system from Microsoft Research
- Relies on modern programming language features
  - Combination is novel, but individual pieces are well understood

Discussion

- Real-time and embedded systems have unique constraints; strong correctness concerns
- Low-level programming model was necessary for efficiency – alternatives for modern systems?

- Further reading:
    - J. Shapiro, “Programming language challenges in systems codes: why systems programmers still use C, and what to do about it”, Proc. 3rd workshop on Programming Languages and Operating Systems, San Jose, CA, October 2006. DOI:10.1145/1215995.1216004
    - G. Hunt and J. Larus. “Singularity: Rethinking the software stack”, ACM SIGOPS OS Review, 41(2), April 2007. DOI:10.1145/1243418.1243424
    - Both papers will be discussed in tutorial 3