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Reproducing System Software Research
A Case Study

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Motivation

- Reading a paper doesn’t imply you understand it
  - Details might be missing or unclear
  - Details of a paper might be
    - …unintentionally or intentionally incorrect
    - …described but never implemented 😮
- *All these things can slip through the usual peer review process for conferences and journals!*
- Reproducibility of research results is important
  - Gives confidence that work exists and is useful
  - Can provide a basis to build own research upon
- (Relatively) Recent trend: require reproducibility
  - Delivery of paper + "artifacts" = code, data, …
  - Different levels of artifact evaluation
- *What is the situation for systems papers?*

Levels of usefulness

Functional	Reusable	Available	Replicated	Reproduced
No Badge				
Artifacts documente d, consistent, complete, exercisable , and include appropriate evidence of verification and validation	Functional + very carefully documented and well-structured to the extent that reuse and repurposing is facilitated. In particular, norms and standards of the research community for artifacts of this type are strictly adhered to.	Functional + placed on a publicly accessible archival repository. A DOI or link to this repository along with a unique identifier for the object is provided.	Available + main results of the paper have been obtained in a subsequent study by a person or team other than the authors, using, in part, artifacts provided by the author.	Available + the main results of the paper have been independently obtained in a subsequent study by a person or team other than the authors, without the use of author-supplie d artifacts.

Example: Persistence from app to hardware

- Persistent operating systems are no new invention
  - "hot" research topic in the 1980s/90s
    - Smalltalk, Lisp (Interlisp, Symbolics), IBM OS/400
    - Eumel/Elan and L3 [1], BirliX [2]

EUMEL

L3

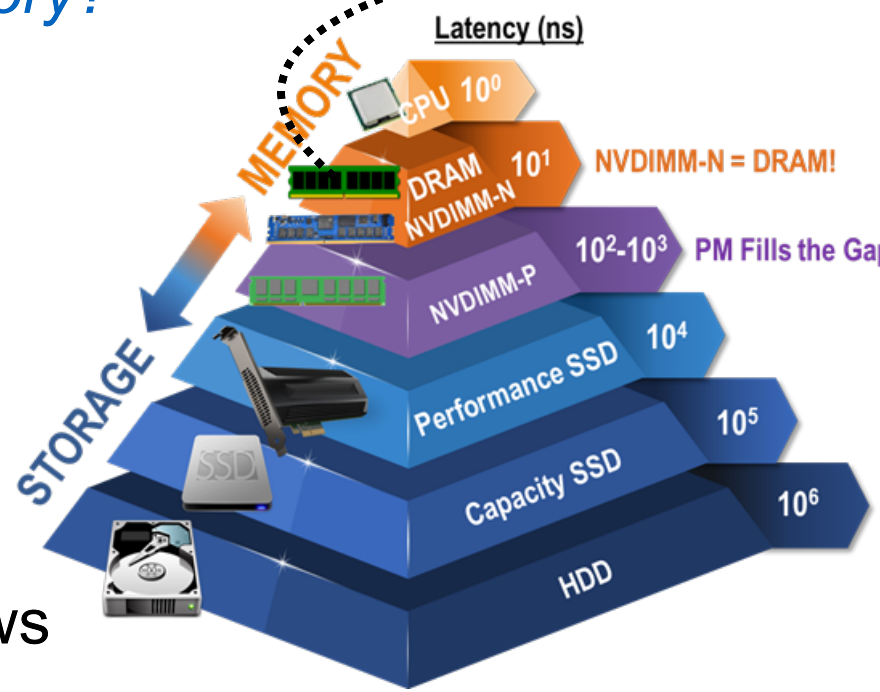
symbolics inc.

- Implementation of persistence
  - All system state was kept in RAM
- *Snapshots* generated on non-volatile storage
  - …when shutting down the system
    - crashes ➛ start from initial (boot) state
  - …initiated manually or at regular intervals
    - tradeoff overhead ↔ amount of work lost

What's the state in 2021?

- Persistent, byte-addressable main memory is available now

- *Can we implement persistent system images on top of persistent main memory?*



- Several *challenges*, e.g.
  - Persistence semantics
    - Ensure consistency
    - Non-persistent state
  - Protection
    - Heap and stack overflows

Persistence challenges: protection

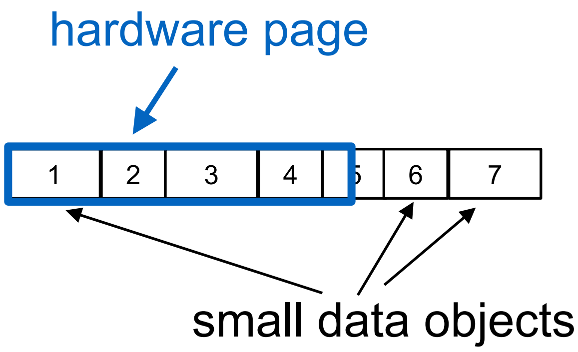
- *Wanted:* protection for small regions of memory
  - e.g. objects on stack and heap
  - Persistent main memory ➢ persistent errors
- Do we really need this?
  - Is language-based protection not safe enough?
  - *Should the operating system trust the compiler?* [3]

Language-based protection has some significant weaknesses: [4]

- the TCB of a system depending on language protection is larger because now we must trust the compilers and code verifiers as well as the "system" TCB objects provided by the system
- language-based protection has its own performance problems and the optimizations to improve performance introduce subtle security flaws

Hardware-based protection today

- Problems with current virtual memory
  - Fixed page size (e.g. 4kB)
  - Trend towards even larger sizes
  - Protection is tied to translation



- Look for existing fine-grained approaches
  - *Are we just trying to reinvent the wheel?*

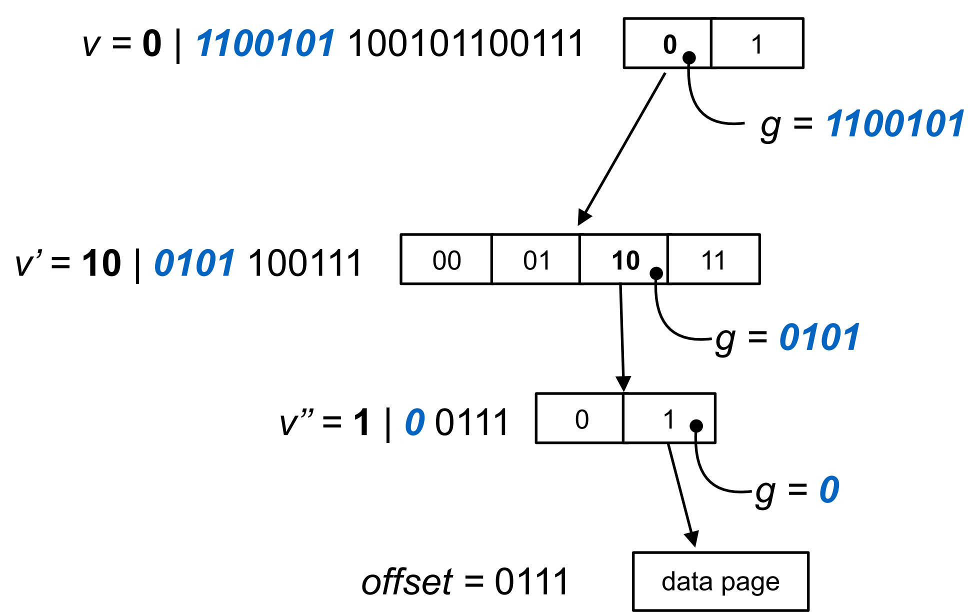
- One approach: Liedtke's *Guarded Page Tables (GPT)* [5]
- GPT properties to investigate for today's systems
  - Page table depth versus page size?
  - Effects of small pages on TLB miss rate?
  - How can we implement a GPT approach today?

Guarded page tables

- GPTs supplement page table entries (PTEs) by a *guard*
  - Guard = bit string of variable length

Translation steps:

1. PTE is selected by the highest part of the virtual address
2. Selected entry contains a pointer *and the guard g*
3. If *g* is prefix of the remaining virtual address
   - Translation continues with remaining postfix
   - …or terminates with postfix as page offset



How it started…

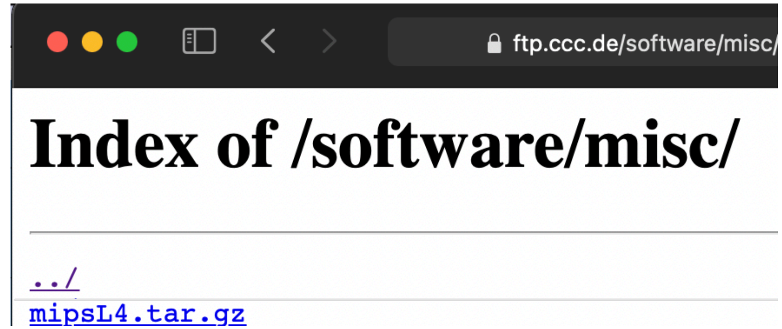
- Idea: reproduce GPT ideas from Liedtke's papers [5]
  - Sometimes, papers are as sparse as GPT address spaces 😀

- Can we find details in Liedtke's PhD thesis [6]?
  - Not available in electronic form
  - A printed copy can be found in the NTNU *library*!

- Were GPTs ever implemented?
  - Yes, at UNSW in L4/MIPS and L4/Alpha
  - Useful details in the related paper [7] and docs [8]

Finding and compiling L4/MIPS

- Finding the source code
  - not so easy…
  - Finally, found four versions
    - 71, 75, 79, 81



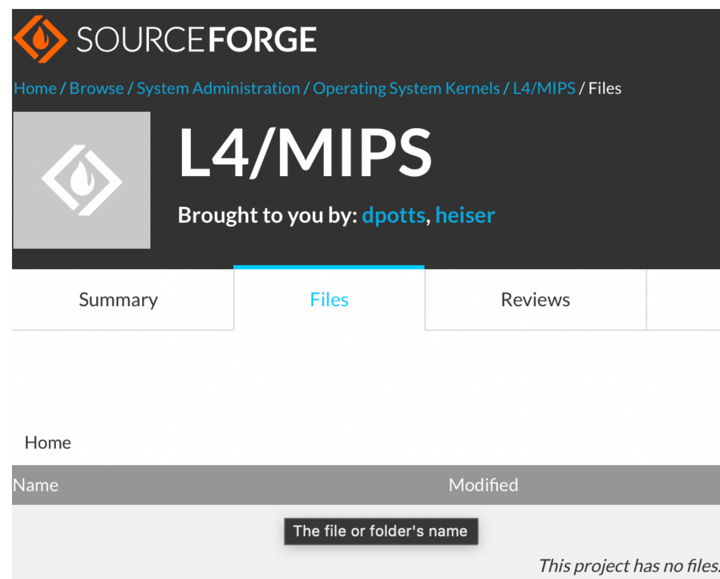
This document is an attempt to document the internal structure of L4 and its operations. It is based on the L4 implementation for the MIPS R4x00 (L4/MIPS), kernel version 79 (February 1999). The document is meant as

```
README for L4/MIPS

Prequisites before building

1) You need mips-sgi-irix6 cross-compiler development tools.
```

- This used gcc-2.8.1 from 1998…
  - Doesn't compile on current Linux
  - Set up a Debian 3.0 x86 VM
  - The compiled cross-compiler + L4 tools runs on current Linux!



Hardware platform

- *Problem when reproducing system software*
  - The OS runs directly on the hardware…
- Special hardware required for implementing GPT
  - Software TLB miss handler instead of hardware PT walk
  - Only implemented on (early) MIPS and Alpha
- What machines did L4/MIPS run on?
  - *"The kernel is stable since August 1997, with minor enhancements and bug fixes since. It has been tested on an R4600-based SGI Indy, on the Algorithmics P4000i prototyping board, as well as on the R4700-based U4600 system developed at UNSW as a research and teaching platform."* [8]
- Where can we find specialized 25 year old hardware?

Running L4/MIPS

- NTNU's "datamuseet" helps: found an SGI Indy!
  - Unfortunately, it has the "wrong" CPU (R5000) [7]:

The kernel code described in this document is for a uniprocessor R4600/R4700 system. There are a number of minor differences between various processors of the R4x00 family. For the purpose of kernel code, no significant

Other related processors, such as the R5000 and the R10000 will probably run L4/MIPS without major changes. Particularly the R5000's MMU seems to be similar enough to the R4x00 to allow the code to run virtually unchanged. However, the R5000 and R10000 are multi-issue CPUs, and no attempt has been made in the kernel to

Hardware is hard…

- Emulators are an alternative
  - Sulima [9] https://www.jantar.org/sulima/
  - MAME Indy emulation https://sgi.neocities.org
- MAME runs IRIX… but does not boot L4/MIPS
- Sulima was built to run L4/MIPS – three versions online:
  - sulima-mips-020813, sulima-030910, sulima-src-051124
  - The first one actually works with L4/MIPS!

```
Sulima v1.0.0 built on Mar 13 2021, 18:05:47
Copyright (C) 1998-2000 Patryk Zadarnowski

Avaliable modules:
Sulima: koala-R4600     R4600 MIPS III Processor
Sulima: MIPS64SimpleBus A minimal MIPS64 memory and I/O controller.
Sulima: ZilogESCC       Zilog Enhanced Serial Communication Controller
Sulima: MT48Tx2         T48T02/12 Timekeeper(R) RAM
Sulima: ROM             Basic ROM module.
Installed modules:
Sulima: nvram
Sulima: serial
Sulima: rom
Sulima: bus
Sulima: cpu                  (CPU)
Resetting hardware....
Beginning simulation....
Sulima: Simulation started (1 CPU).
Loader: relocating 0x100f8 bytes from 0xFFFFFFFFBFC012F8 to 0xFFFFFFFF80050000
Loader: relocating 0x00b40 bytes from 0xFFFFFFFFBFC113F0 to 0xFFFFFFFF80061000
Loader: relocating 0x24000 bytes from 0xFFFFFFFFBFC11F30 to 0xFFFFFFFF80063000
Loader: jumping to 0xFFFFFFFF80060018
Interrupt serial driver at 0x1002000000060401
main:   Mapping tester  0x1002000000080001
main:   This test will take a while, please be patient.
main:   L4uK version 80 build 6
main:   Memory size 64MB
main:   L4 reserved below 0x64000 and above 0x3999000
main:   serial       addr 0x64000    size 0x5000
main:   map_main     addr 0x69000    size 0x4000
main:   map_child    addr 0x80000    size 0x4000
main:   child map_child    addr 0x80000    size 0x4000     entry 0x82d08
main:   map_gchild   addr 0x84000    size 0x3000
main:   grandchild map_gchild   addr 0x84000    size 0x3000     entry 0x85ed0
main:   got  0x80000
main:   got  0x81000
main:   got  0x82000
main:   got  0x83000
main:   got  0x84000
main:   got  0x85000
main:   got  0x86000
main:   got  0x87000
main:   got  0x88000
main:   got  0x89000
L4 KERNEL DEBUGGER: break
TCB BASE: 0xc0000000000c0000
KDBG> pgpt
v = 0x64000 pte0 = 0x64780 pte1 = 0x65780
v = 0x66000 pte0 = 0x66780 pte1 = 0x67780
v = 0x68000 pte0 = 0x68780 pte1 = 0x0
v = 0x1c800000 pte0 = 0x1c800580 pte1 = 0x0
v = 0xc000000000000000 pte0 = 0x487c0 pte1 = 0x496c0
v = 0xc000000000040000 pte0 = 0x477c0 pte1 = 0x496c0
v = 0xc0000000000c0000 pte0 = 0x3ffc7c0 pte1 = 0x496c0
v = 0xc000000000100000 pte0 = 0x3ffb7c0 pte1 = 0x496c0
v = 0xc000000020000000 pte0 = 0x487c0 pte1 = 0x496c0
entries = 72 leaf = 9  guard = 4
depth sum = 25
KDBG>
```

…how it's going

- L4/MIPS compiles and can be run in the Sulima emulator
  - Allows *qualitative* analyses
    - e.g. examining page tables structure, TLB content
  - Allows *modifications*
- What's missing?
  - More precise emulations for *quantitative analyses*,
    e.g. timing – Sulima is not cycle-exact, does not emulate the memory hierarchy
  - Application and benchmark code
- Future ideas (for student projects):
  - Run Mungi [10] or some older L4-based example student projects

SDIOS06 *(T. Bingmann, M. Braun, T. Geiger, A. Maehler - University of Karlsruhe)*
This is a toy operating system developed during the "System Design and Implementation" course 2006 at the University of Karlsruhe.

SC/OS *(S. Hack, C. Ceelen - University of Karlsruhe)*
SC/OS is an experimental multi-server toy operating system using Flick. It was built by two students in the course "System Design and Implementation" in summer 2001.

ChacmOS *(A. Haeberlen, C. Schwarz, M. Völp, H. Wenske - University of Karlsruhe)*
ChacmOS is an experimental multi-server toy operating system. It was built by four students in the course "System Design and Implementation" in summer 2000.

Takeaways

- Many systems publications from the 1980s/90s are not reproducible
  - No hardware or simulator available
  - No code was published
- The UNSW L4 project already applied good practices
  - Suffered from "bit rot" and unavailability of old web sites
  - Documentation for code in addition to papers [8]
  - Simulator available (no quantitative analyses)
- Compiling the code took some effort (cross-compiler setup)
  - *We need to archive the software source code, compiled binaries and the development environment*
- The OS (source code) alone is not enough
  - Publish binaries of the OS to check if local compilation is equivalent to code used for a publication
  - Also publish application and benchmark code

Future work

- Teach students to work with system code
- Current experiment at NTNU
  - Seminar with system software topics
  - Select small and (relatively) simple papers
- Enable students to *understand* a paper
  - …by *reproducing* a central idea from a paper
    - e.g. tickless scheduling, redundancy, new approaches to syscalls, ACLs, …
- Based on MIT's xv6 OS running on RISC-V
  - qemu or Nezha Allwinner D1 board
  - https://github.com/michaelengel/xv6-d1
  - Alternatives: Raspberry Pi or x86

Available + the main results of the paper have been independently obtained in a subsequent study by a person or team other than the authors, without the use of author-supplie d artifacts.

Surprises…

Chapter 7

Other Stuff (Provisional)

7.1 Scheduling

Discuss wakeup queue structure.

Blah blah blah…

7.2 Interrupts

7.3 Initialisation

7.4 Sigma Zero

"Mut zur Lücke"? [8]

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