Dual Execution and Comparison For Genode Components Performance Penalty And Challenges

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Outline

- Introduction to DWC
- Systematic process element replay
- Possible Usages and advantages compared to other fault tolerant techniques
- Genode deterministic Replay
  - Current state
  - Performance Impact
- Remaining works

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Execution replay
Introduction to DWC fault Tolerance

- DWC = Double execution With Comparison
- purpose : Detect transient errors and take actions to recover
- Double execution can happen
  - In parallel (simultaneously or with one execution slightly delayed) or in sequence
  - At instruction level or at set of instructions level
- To be effective, execution replay must be deterministic
  - Run the same code with the same initial data and environment
- Field of application : fault tolerant system, debugging, software verification, hardware testing …

Examples

- Primary-backup hypervisor based fault tolerance system (1)
- Virtual machine based security system : Revirt (2)
- Hardware assisted deterministic Replay : Capo (3)

1. Bressoud, T. C., & Schneider, F. B. (1996). Hypervisor-based fault tolerance. *ACM Transactions on Computer Systems (TOCS)*, *14*(1), 80-107.
2. Dunlap, G. W., King, S. T., Cinar, S., Basrai, M. A., & Chen, P. M. (2002). ReVirt: Enabling intrusion analysis through virtual-machine logging and replay. *ACM SIGOPS Operating Systems Review*, *36*(SI), 211-224.
3. Montesinos, P., Hicks, M., King, S. T., & Torrellas, J. (2009, March). Capo: a software-hardware interface for practical deterministic multiprocessor replay. In *ACM Sigplan Notices* (Vol. 44, No. 3, pp. 73-84). ACM.

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Our model : Systematic processing element replay

- Here, the execution replay is
  - applied to a set of instructions
  - is limited in time (< hundreds of µs), short enough so that it may not experience more than one error.
- The kernel is modified so that it systematically:
  - Divides any process in short "processing elements" (PE),
  - runs them twice and
  - compares the "result" :
    - OK: commit the result and start the next PE,
    - KO: restart the current PE
    - Unexpected exception during one of the executions: restart the current PE

operational transaction - OT

Deterministic PE

- PE execution is **atomic and idempotent :** No interaction with the outside world.
- PE is delimited by IO, time dependent instructions (RDTSC), system calls, or any exception (page fault, protection fault, …) raised by the user process.
- Main goal :
  - Detect transient fault and correction techniques

OT Processing

- The “result” is composed of:
  - All modified memory pages (P_1, $P_{2,}$ …, P_m) and
  - User process related registers - UPRR (General Purpose Registers, RIP, SP, …)
- n^{th} Processing Element is called e_n
- $e_{n,i}$ $(i \in \{1,2\})$ is the i^{th} execution of e_n
- $P_{m,i}$ is the modified P_m during the i^{th} execution of e_n
- $P_{m,0}$ is the unmodified version of P_m before the first execution of e_n

OT Processing

- Before the $e_{n,1}$, save all UPRR –> R_0 and process memory to PM_0 (Pages 1, 2, …, m)
  - Set process memory to Read-Only to keep trace of altered pages : will cause page faults
- During $e_{n,1}$, PM_1 (collection of all altered pages) is progressively constructed
  - At every page fault, the concerned page is replaced by a new page with same content and RW right and added to PM_1 ($P_{1,0}$ --> $P_{1,1}$, $P_{2,0}$ --> $P_{2,1}$, ..., $P_{m,0}$ --> $P_{m,1}$) : **Copy $P_{j,0}$ to $P_{j,1}$**

OT Processing

- At the end of $e_{n,1}$, and before starting $e_{n,2}$
  1. We replace all altered pages by new ones, but with RW right : PM_2 ($P_{1,0}$ --> P_{12}, $P_{2,0}$ --> P_{22}, ..., $P_{m,0}$ --> $P_{m,2}$) : **Copy $P_{j,0}$ to $P_{j,2}$ (No page fault is expected)**
  2. Save all UPRG –> R_1
  3. Flush the caches
- At the end of $e_{n,2}$, compare one by one all Pages $P \in PM$ ($P_{1,1}$ and $P_{1,2}$, $P_{2,1}$ and $P_{2,2}$, ..., $P_{m,1}$ with $P_{m,2}$) and all registers in UPRR
  - If comparison OK: Set PM_0 to PM_1 (or PM_2) and proceed to next OT
  - If comparison KO: restart the current OT

Implications

- This involves to:
  - Copy 3 times, word by word up to 10 memory frames, 4 kB each,
  - Compare, word by word, up to 10 memory frames, 4 kB each.
    - The working sets vary usually from 0 to 10 frames, according to our tests
  - Flush the caches
- And all of these
  - In no more than **certain time limit** (200 µs for example) while
  - Fulfilling **real time constraints** of some applications.

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State of the concept

- Systematic processing element replay has already been applied to process running on bare metal (without OS) as fault tolerance technique against Single Event Upset in small embedded system(1)
- On-going work by E. Assogba, to port to Operating System level
- We are trying to port it virtual machine support level as proof of concept to enable the use of any unmodified OS.

(1) Laurent Lesage and al, "A software based approach to eliminate all SEU effects from mission critical programs," 12th European Conference on Radiation and Its Effects on Components and Systems (RADECS), 2011, pp. 467–472.

Limiting process execution time

- The process releases the CPU (traps or faults) before granted time limit is reached
  - Just restart the PE from its starting point
  - $e_{n,2}$ must normally be exactly the same as $e_{n,1}$
- The process exhausts its granted time
  - A timer interrupt is issued at time limit during $e_{n,1}$: N instructions have been executed then
  - $e_{n,2}$ runs with Performance monitoring interrupt armed on instruction counter overflow.
  - Make sure the same number of instructions is executed.
- Proceed to comparison phase.
- I/O instruction, MMIO and time dependent Instruction (eg. rdtsc) stop the PE

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Genode deterministic Replay

- When applying Systematic processing element replay to Genode framework, we are interested in the following concerns:
  1. Will an OS, in a virtual machine, be run in this fashion while satisfying to its service constraints toward user processes?
  2. What will be the overall overhead?
  3. How long can we shorten the atomic execution (OT) time with a critical charge of work in the running virtual machine?

Results
OT execution (1/2)

- The implementation is not totally finished but some meaningful results are already available

t1 : first run

t2 : second run

r : time to restart – kernel

cc: time to compare and commit

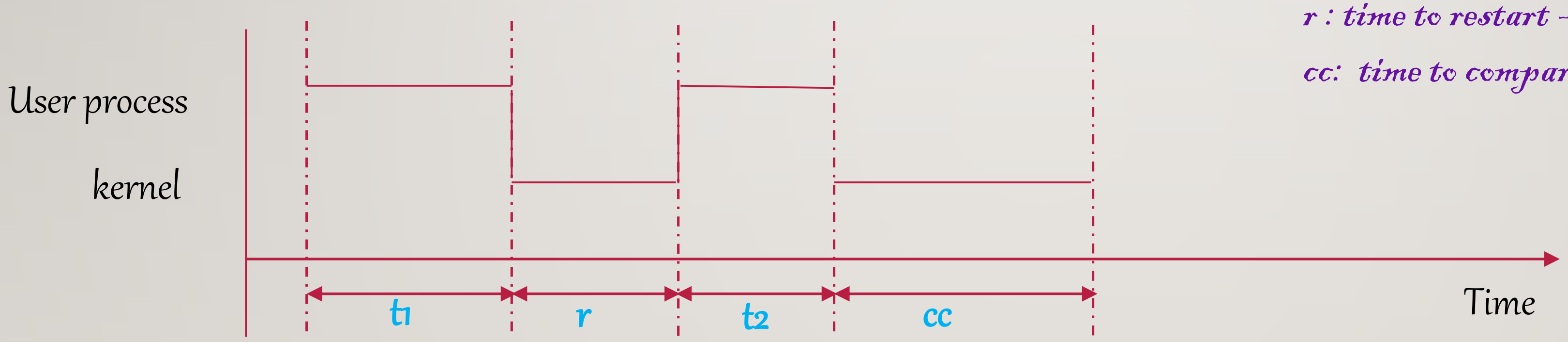
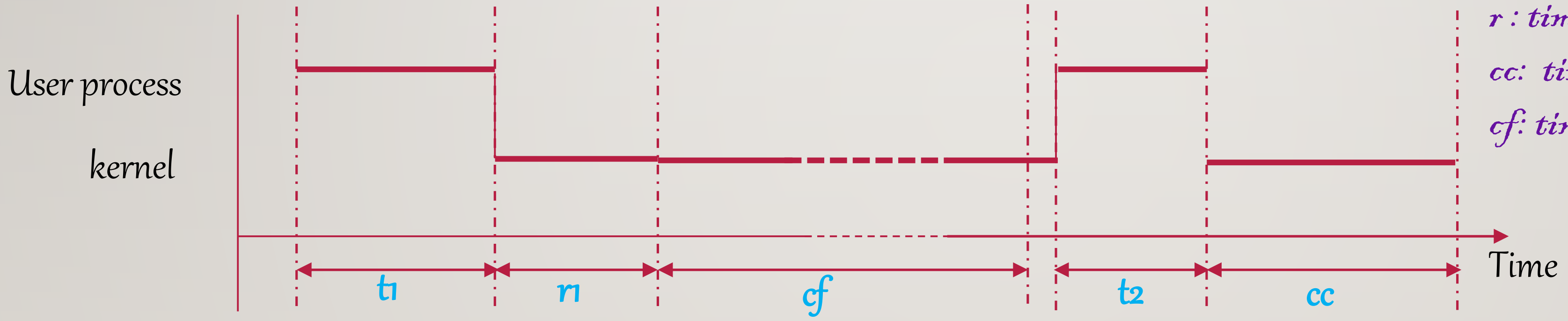


Fig1 :A correct OT execution with no cache flush

- The second run is always shorter than the first (because no page fault is expected). This run may be considered as a normal Genode process execution

Results
OT execution (2/2)



t1 : first run

t2 : second run

r1: first run treatment

r : time to restart – kernel

cc: time to compare and commit

cf: time to flush the caches

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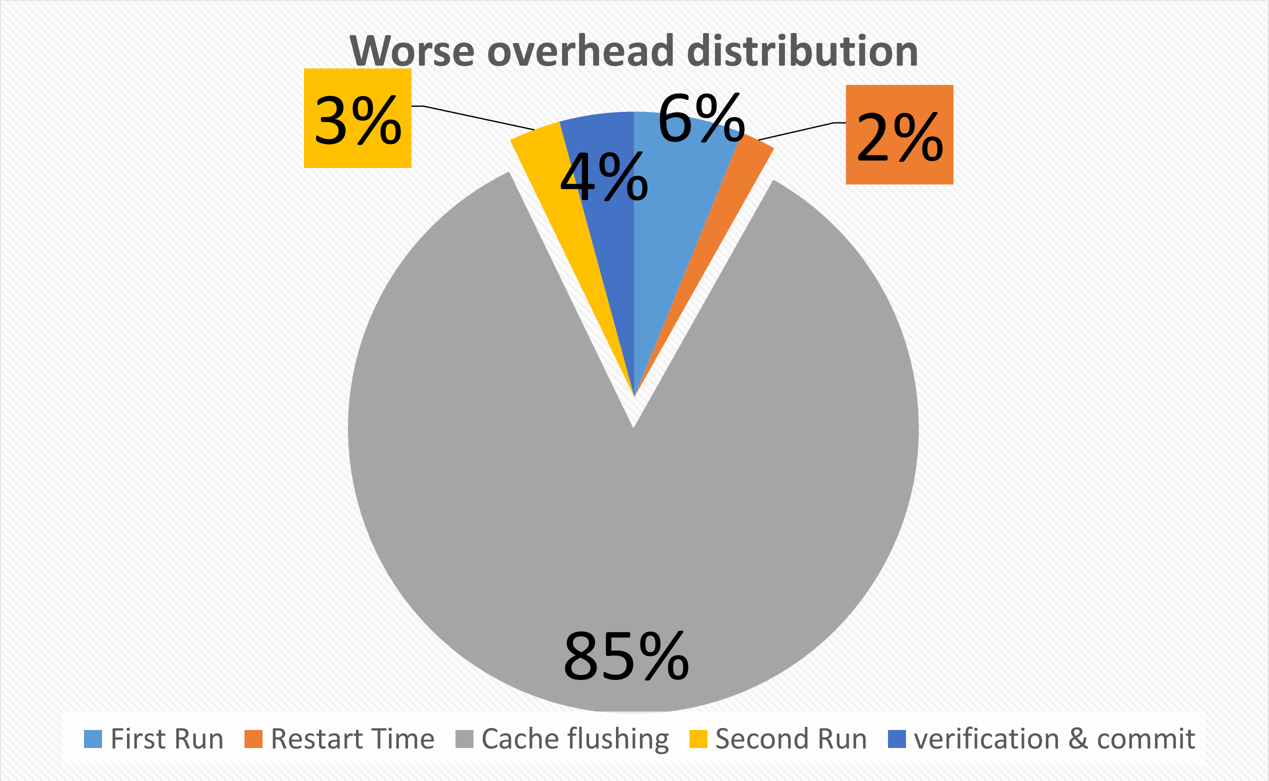
Benchmark

- Benchmark execution not possible yet (virtual machine not supported yet)
  - Genode normal execution is approximated by the second run.
  - the overall performance penalty can be expressed by the ratio of the total execution time divided by the second run time.

$$\tau = \frac{100\ * (t_1 + r1\ +\ cf + t_2 + cc)}{t_2}$$

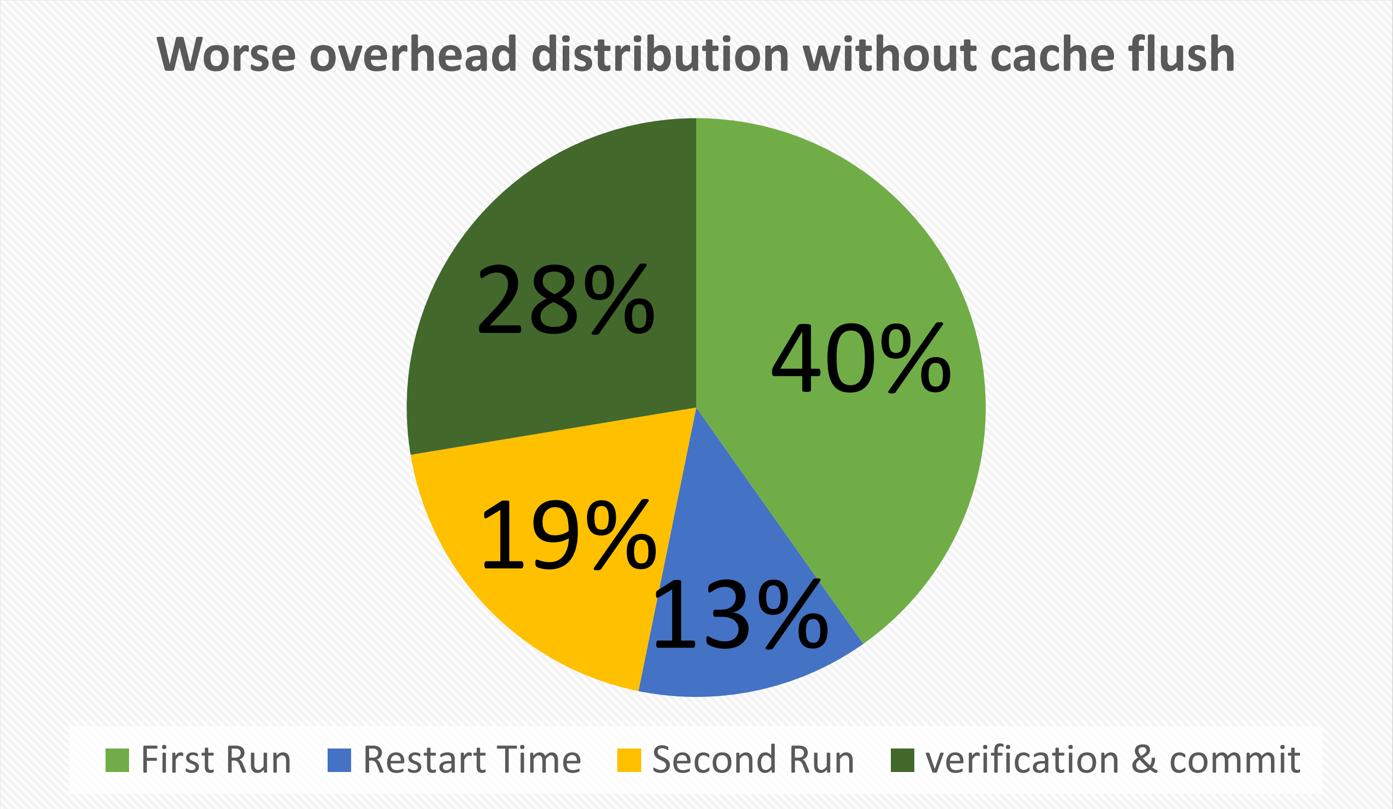
- Current state only works for the Genode initialization phase.
- The system starting phase (initialization) is certainly the worse case since this time, processes are expected to make frequently a lot of system calls.

Performance penalty
When PE ends at system call or exception (1/2)



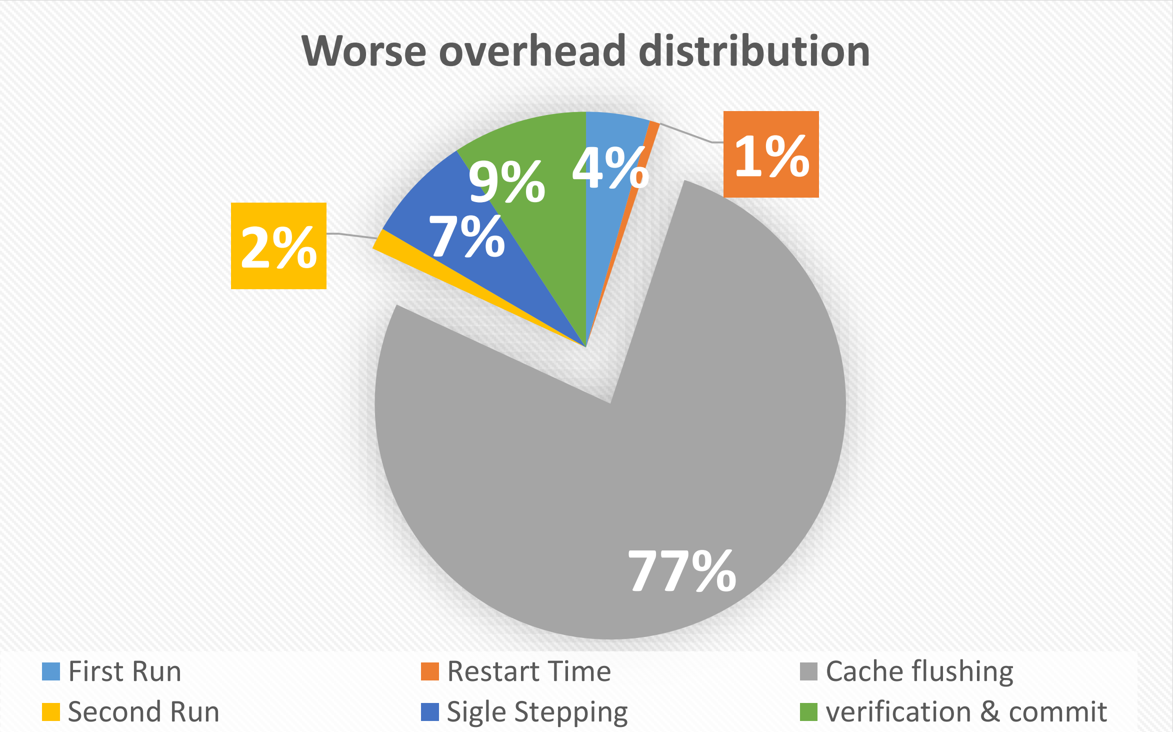
Overhead : 3400%
Total execution Time : 237 µs

Performance penalty When PE ends at system call or exception (2/2)



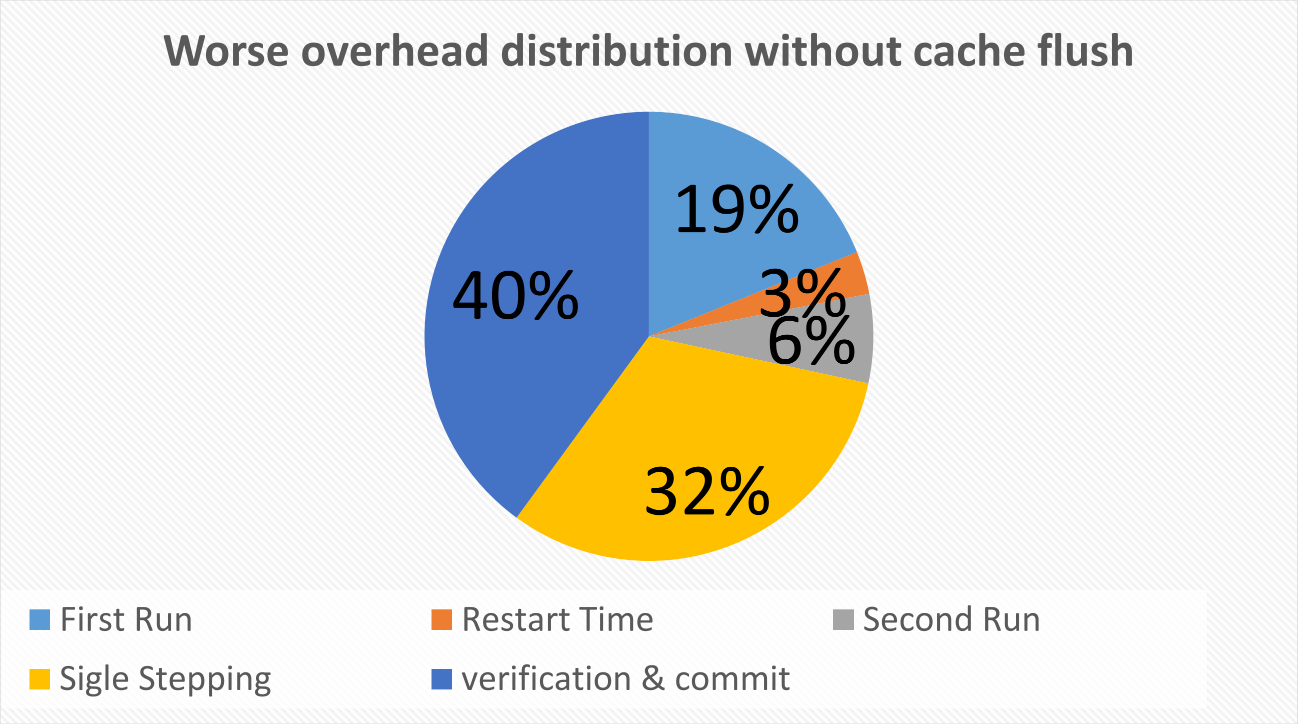
Overhead : 527%
Total execution Time : 36 µs

Performance penalty When PE stops after exhausting its granted time (1/2)



Overhead : 6221%
Total execution Time : 242 µs

Performance penalty
When PE stops after exhausting its granted time (2/2)



Overhead : 263%

Total execution Time : 56 µs

Overall performance overhead during the booting

- Normal Genode demo scenario Boot ≅ 14s (Lenovo x230, core i5, 8 GB)
- With cache flushing
  - Dual execution Mode : 7 min 40s
  - Performance penalty : 3285% with cache flushing
- Without cache flushing
  - Dual execution Mode : 16s
  - Performance penalty : 114%

Current issues

- Instructions counting
  - Until now we have not dealt yet successfully with all the peculiarities of the Intel instruction counter feature (compared to AMD).
  - Sometime, for the same Processing element, the number of instructions executed during the first and the second are not the same.
- Page fault appears randomly when the system is fully started (after the initialization phase) independently from the instruction counting problem

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Future work

- Understand the cause of page fault and correct the problem
- Optimize cache flush operation
- Make full virtual machine support
  - Run the Heeselicht scenario (Linux running In Genode running on DWC featured Nova Kernel)
  - Compile GCC and Linux kernel in the Linux virtual machine
  - Run some benchmarks in Linux Virtual machine

Thank You