Replay Debugging: Leveraging Record and Replay for Program Debugging

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Motivation: Bug Reproduction is Difficult

Especially for bugs in production runs

Due to

- Complex inputs
- Non-deterministic timing in concurrent programs

Record and Deterministic Replay (**RnR**) can help

- **Recreates** execution of a program
- **Record**: capture non-deterministic events in a log
- **Replay**: use the log to recreate the exact same execution

Problem: Current RnR solutions are not quite suitable as debugging tools.

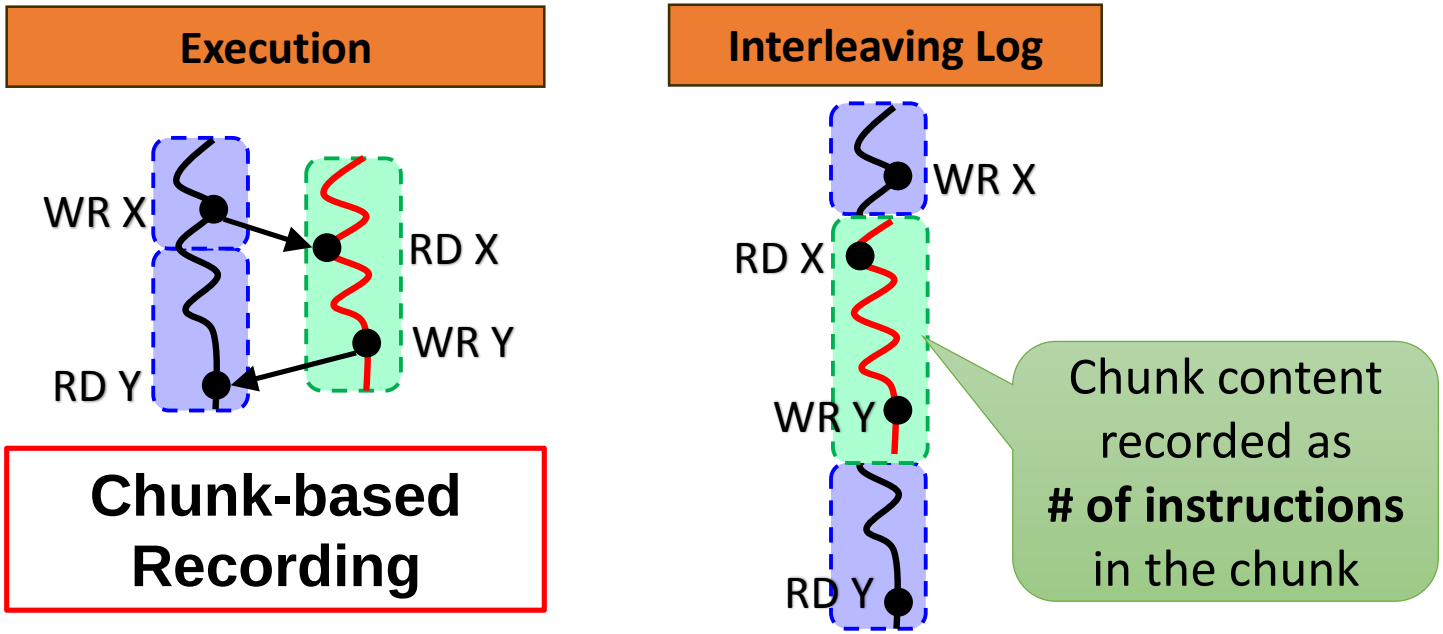
RnR Logs in QuickRec [ISCA'13]

Captured in OS kernel

Input Log: Program/OS interactions
- System call results
- Data copied to application buffers by OS kernel
- Signals, …

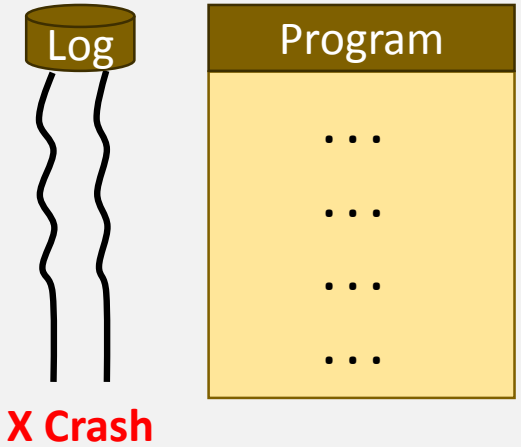
Captured using special HW

Memory Access Interleaving Log
- Inter-thread dependences



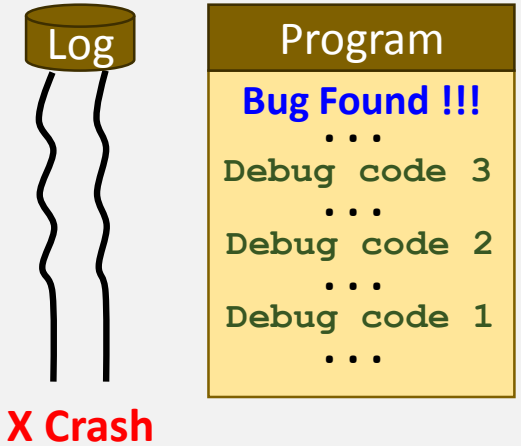
Problem: Naïve RnR not Enough for Debugging

Replay only reproduces the buggy execution



Not enough! need to augment the code for diagnosis

Replay Debugging: Augment the code and still be able to replay the log



Augmented code cannot be replayed using the recorded log:

- Different input events
- Different sequence of insts

Enables fast & deterministic convergence to the source of the bug

Effective Bug Diagnosis

…Needs the ability to

- Write debug code as if part of the same program (may be inlined with main code)

```
int a = /* program code */;
#ifdef DEBUG
  printf("a is %d", a);
#endif
```

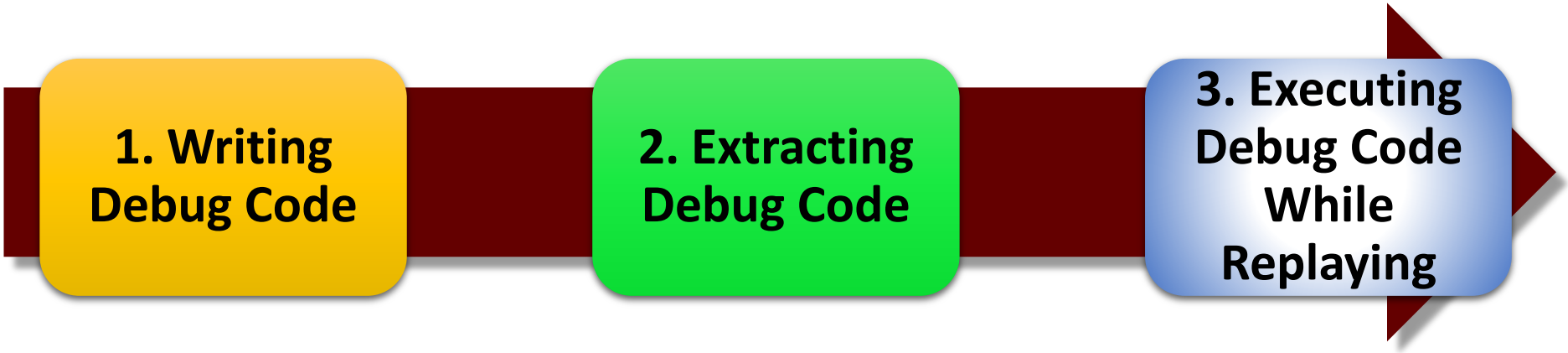
  - Access main program state
  - Call main program functions
  - Output results of debug code
  - Have debug-only state in the debug code, e.g.,
    - Local and global variables, heap-allocated objects, shadow data structures

How to enable all of this without breaking replay?

Contribution: Replay DeBugging (RDB)

- A methodology for guaranteed deterministic replay in presence of debug code
  - → **One can debug a non-deterministic bug deterministically**
- A design combining compiler technology + replay mechanisms
  - Implementation using LLVM and Intel's Pin
- Seamless debugging experience for the programmer
  - RDB debug code very similar to ordinary debug code

RDB Approach: Overall View



Programmer adds debug code to program source code

Compiler extracts debug code and generates two binaries

- One contains original, unmodified code
- Other contains the debug code

Replay tool automatically invokes debug code at correct points while replaying the log

Modified LLVM Compiler

1. Programmer Writes Debug Code

Debug Code:

Should be marked using special markers

Can read main program state

Can invoke main program functions

Should not write to main program state (directly or indirectly)

To guarantee replay remains deterministic

Can have its own state (local, global and heap)

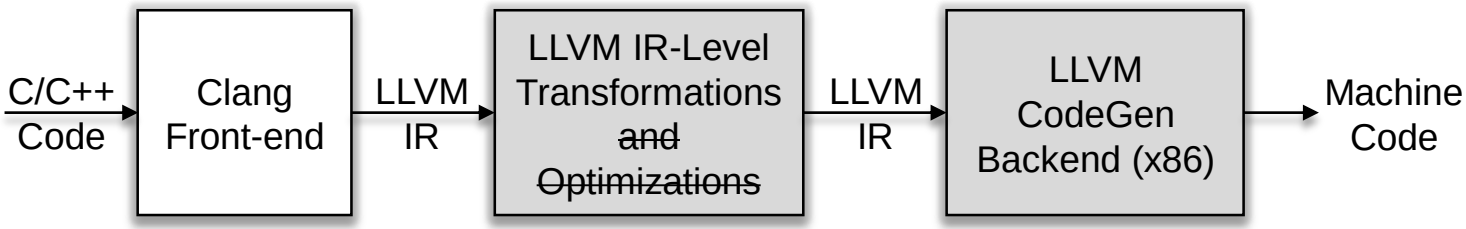
Use the same virtual address space as the main code

- E.g., debug vars can point to main data

Can use runtime library functions

- E.g., `printf()` or `malloc()` from `libc`
- Will have its own instance of runtime libs during replay

2. Compiling the Augmented Code



LLVM Compiler Flow

Front-end creates unoptimized LLVM IR from source code

Optimizer transforms LLVM IR to optimized form

- We assume all optimizations are disabled for now

CodeGen generates machine code

We modify the last two

2.1. Generating Initial LLVM IR

No Changes to the Front-end

```
void main(void) {
  char c;
  c = getchar();
  rdb_begin
  printf("c is '%c'\n", c);
  rdb_end
}
```

Clang Front-end

```
@.str = "c is '%c'\n"

void @main() {
 %c = alloca i8
 %_tmp0 = call @getchar()
 store %_tmp0, %c
 call @__rdb_begin()
 %_tmp1 = load %c
 call @printf(@.str, %_tmp1)
 call @__rdb_end()
}
```

Instrumented C Code

LLVM IR

2.2. Extracting the Debug Code

Extract the debug code

```
@.str = "c is '%c'\n"

void @main() {
 %c = alloca i8
 %_tmp0 = call @getchar()
 store %_tmp0, %c
 call @__rdb_begin()
 %_tmp1 = load %c
 call @printf(@.str, %_tmp1)
 call @__rdb_end()
}
```

LLVM IR (from Front-end)

LLVM IR-Level Transformations

```
@.str = "c is '%c'\n"

void @__rdb_func_1(i8* %arg) {
 %_tmp1 = load %arg
 call @printf(@.str, %_tmp1)
}
```

Extracted Debug Code (LLVM IR)

```
void @main() {
 %c = alloca i8
 %_tmp0 = call @getchar()
 store %_tmp0, %c
 call @llvm.rdb.location(1)
 call @llvm.rdb.arg(1, 0, %c)
}
```

Extracted Main Code (LLVM IR)

FuncID	FuncName
1	__rdb_func_1
2	…

Function Descriptors (C++)

2.3. Generating Machine Code

Generate Machine Code

```
@.str = "c is '%c'\n"

void @__rdb_func_1(i8* %arg) {
 %_tmp1 = load %arg
 call @printf(@.str, %_tmp1)
}
```

LLVM CodeGen Backend (x86) → Debug Code (x86 object file)

Extracted Debug Code (LLVM IR)

```
void @main() {
 %c = alloca i8
 %_tmp0 = call @getchar()
 store %_tmp0, %c
 call @llvm.rdb.location(1)
 call @llvm.rdb.arg(1, 0, %c)
}
```

Extracted Main Code (LLVM IR)

LLVM CodeGen Backend (x86) → Main Code (x86) + Symbols for Location Markers

FuncID	Position	Class	Info
1	0	Stack	(SP, -20)
2	0	…	…
2	1	…	…

Argument Descriptors (C++)

3. Replay Tool Invokes Debug Code

Replay implemented using Intel's Pin (similar to QuickRec)

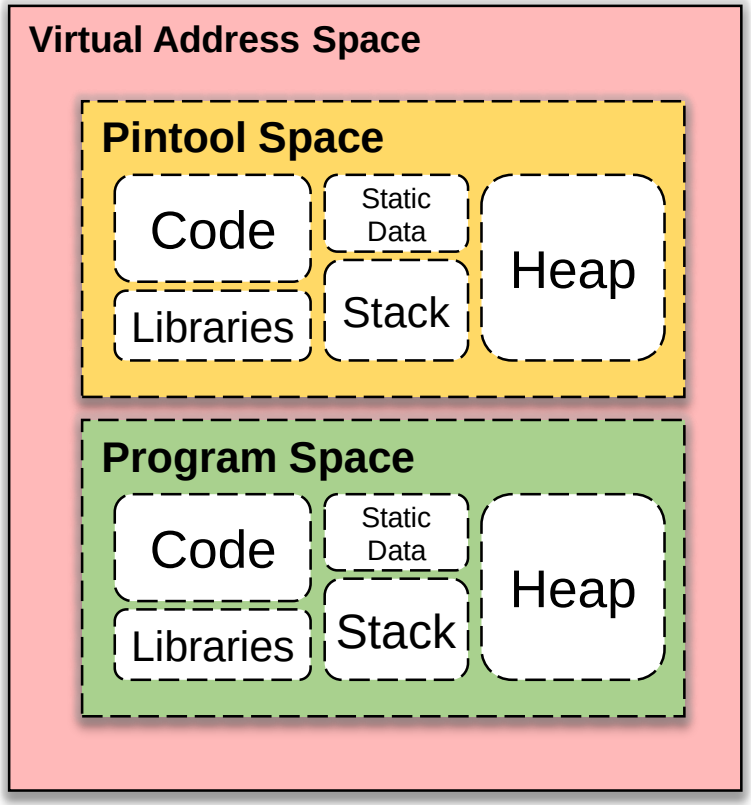
- A binary instrumentation infrastructure

Anatomy of Pin

- Program and Pintool in the same address space
- Pintool is use-case specific

Our pintool, RdbTool, does two things:

- Replays the log
- Invokes debugging code



3. Replay Tool Invokes Debug Code

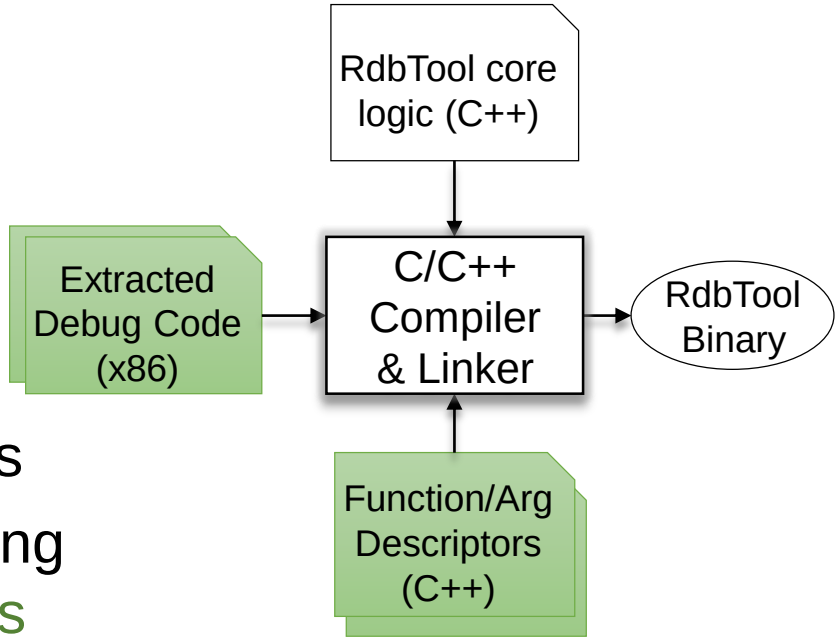
To replay, RdbTool

- Instruments system calls to inject program inputs
- Counts # of insts to enforce recorded interleaving

To invoke debug code, compile debug code into RdbTool

RdbTool then

- Sets breakpoints at debug markers
- Finds and invokes debug code using *Function* and *Argument* descriptors



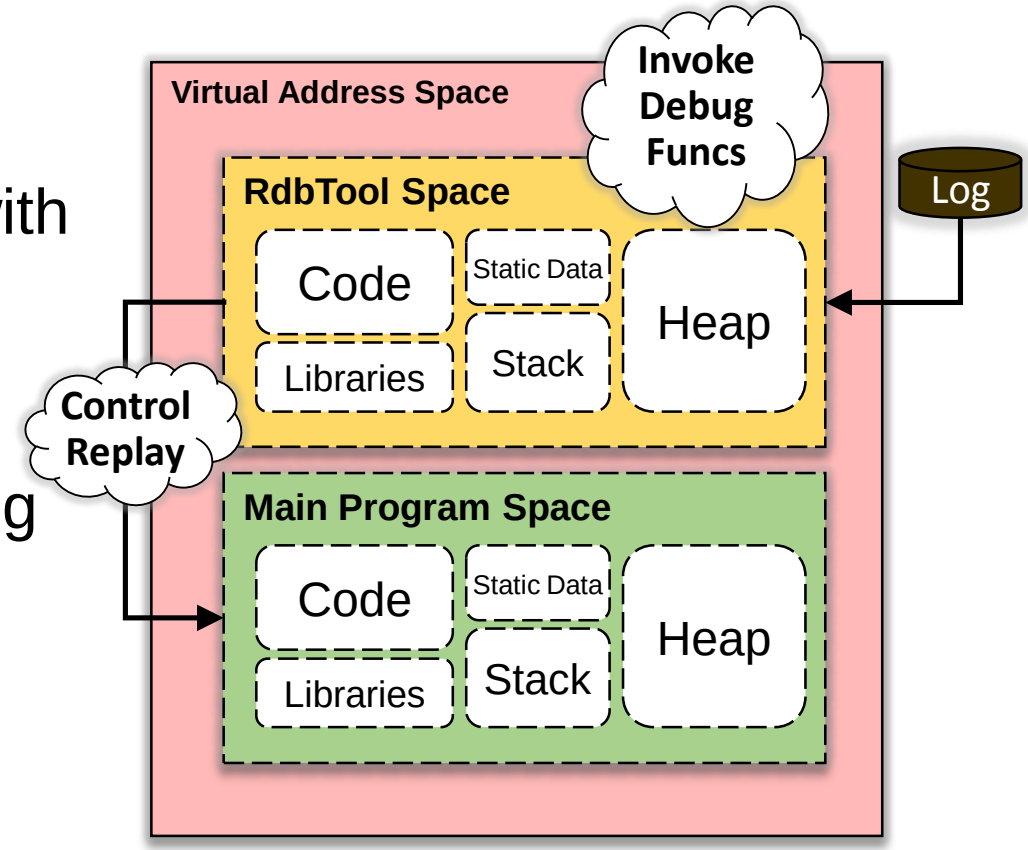
3. Replay Tool Invokes Debug Code

Loads the main code; links it with runtime libraries

Loads the RdbTool; links it with separate runtime libraries

Replays the main code & invokes debug code on hitting a debug marker

Execution is the same as recorded in the log



Problem with Compiler Optimizations

Optimizations will be performed after extracting debug code

May render the debug code invalid

- E.g., may optimize away state needed by the debug code

Work in progress…

```
void f() {
  char c = getchar();
  int a = c ? 5 : 6;
  printf("c is %d\n", c);
  rdb_begin
  printf("a is %d\n", a);
  rdb_end
}
```

Also in the Paper

- Real example of bug diagnosis with RDB
- Support for event-driven debugging (watch points)
- Enforcing read-only access to main-program's memory
- Using gdb together with RDB
- Replay debugging without Pin
- …

Conclusions

Naïve RnR not enough for bug diagnosis

Replay Debugging: A methodology for guaranteed deterministic replay in presence of debug code

- Seamless debugging experience for programmer
- Combines compiler and replay technology
- Proof-of-the-concept implementation using LLVM and Pin

With RDB, one can diagnose a non-deterministic bug deterministically

THANK YOU!