Deterministic Execution in a Java-like Language

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Thesis

A Java-like programming language can be executed deterministically using Deterministic Shared Multiprocessing (DMP) with less overhead than a C-like programming language.

Background

Thread Interleavings

thread 1	thread 2
load count	
store count	
	load count
load count	store count
store count	
	load count
load count	
store count	
	store count

- Source of non-determinism, caused by
  - OS scheduler
  - Cache state
  - I/O delays
- Could execute threads serially, but we can do better

Communicating Instructions

- Load/store instructions to shared memory
- Modify behavior of other threads
- Enforce ordering of communicating instructions, others do not matter

Deterministic Shared Multiprocessing

- Dynamic run-time enforcement of determinism
- Guarantees deterministic ordering of all shared memory accesses for a given input.
- Works on arbitrary code
- Aims to do so without sacrificing performance

How does it work?

- Execute non-communicating instructions during parallel mode
  - Recover parallelism
  - Without interthread communication, thread interleaving does not affect program output
- Serialize execution during interthread communication

Ownership Table

- Used to detect communicating instructions
- Track ownership information for each memory location
  - Private - accessible only to owner
  - Shared - read-only by everyone
- Access unrestricted in serial mode
- Granularity - byte, word, page, etc.

Ownership Graph

solid = `proceed immediately, dotted` = block until serial mode

Previous DMP Implementations

- CoreDet - DMP in software
  - Modified LLVM compiler instruments load/store instructions
  - Arbitrary C / C++ code
  - Linked with run-time framework
  - Ownership table stored in shared memory
  - Reduced serial mode
- **Results:** Average slowdown of 110% - 600%
- Good enough for debugging, maybe for deployment!

DMP Summary

- Execute arbitrary code deterministically
- Deterministic ordering of communicating instructions
- Detect interthread communication in parallel mode, defer until serial mode
- Ownership table used to detect communicating instructions

maTe - a Java-like programming language

1. Pure OO programming language
2. Executed in virtual machine
3. Grammar, instruction set and machine architecture heavily based on Java
4. Single-threaded

Architecture

maTe instruction set

aconst_null	invokespecial
aload	invokenative
areturn	invokevirtual
astore	new
checkcast	newint
dup	newstr
getfield	out
goto	putfield
ifeq	refcmp
in	return

maTe instruction set

aconst_null	invokespecial
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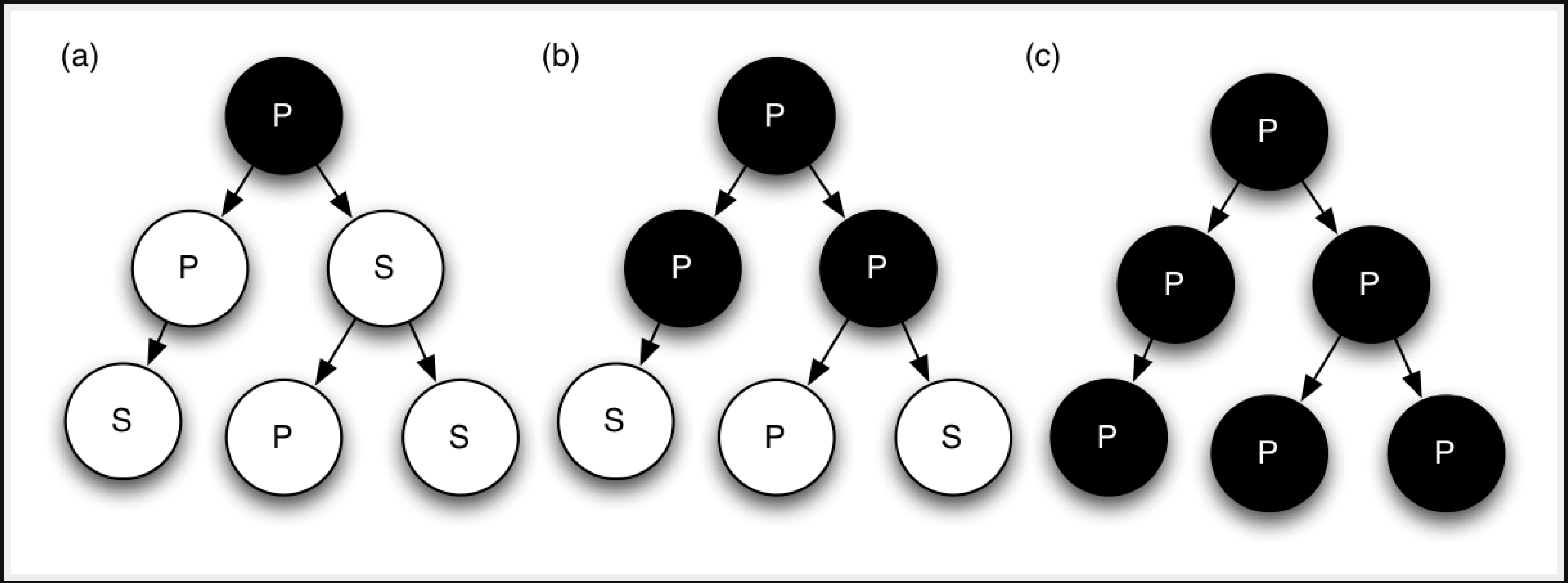
Ownership Depth



Implementation

- Compiler Changes
- Virtual Machine Changes

Compiler Changes

`Real` class (`float` wrapper)

```
class Real extends Object {
        native Real();
        native Real(Real r);
        native Real(Integer i);
        native Real add(Real r);
        native Real subtract(Real r);
        native Real multiply(Real r);
        native Real divide(Real r);
        native Real greaterThan(Real r);
        native Real lessThan(Real r);
        native Real greaterThanEqual(Real r);
        native Real lessThanEqual(Real r);
        native Integer not();
        native Real minus();
        native Real operator + (Real r);
        native Real operator - (Real r);
        native Real operator * (Real r);
        native Real operator / (Real r);
        native Integer operator > (Real r);
        native Integer operator < (Real r);
        native Integer operator >= (Real r);
        native Integer operator <= (Real r);
        native Integer operator ! ();
        native Real operator - ();
        native Integer equals(Object obj);
        native Integer hashCode();
        native String toString();
        native Real squareRoot();
}
```

`synchronized` blocks

```
for (i = 0; i < 10; i = i + 1) {
        synchronized (obj) {
                if (obj.field != null) return obj.field;
        }
}
```

- Use new `monitorenter` / `monitorexit` instructions
- Monitor stack ensures necessary `monitorexit` instructions are emitted for all execution paths.

`Thread` **class**

```
class Thread extends Object {
        native Thread();
        native Object start();  // begin execution of run()
        native Object run();    // overridden by subclass
        native Object join();
        native Object sleep(Integer millisec);
}
```

- Java-based threading model

`Object` class `wait` / `notify` methods

```
class Object {
        native Object notify();
        native Object notifyAll();
        native Object wait();
        native Object wait(Integer timeout);
}
```

- Asynchronous events

Compiler Changes

(aka things you take for granted)

- `for` loops

```
for (i = 0; i < 10; i = i + 1) { ... }
```

- Boolean `&&` and || operators

```
if ((a && b) || (c && d)) { ... }
```

- `!=`, <= and >= operators

```
if (a != b) { ... }
if (a <= b) { ... }
if (a >= b) { ... }
```

Virtual Machine Changes

Multithreaded Architecture

Implementing Threads

- Each `Thread` gets its own PC register & VM stack
- Use `pthreads` threading library
- Use `pthreads_mutex_t` for object monitors

Threading Performance Enhancements

- Remove lots of locks
- Reduce heap accesses
- `Integer` / `String` cache
- Per-thread object reference / free object cache

Implementing DMP in maTe

- Control execution of threads
- Instrument `getfield` / `putfield` instructions
- Track owner of each object
- Prevent blocking system calls

Design Goals

- Enable/disable without recompiling

```
mvm myclass.class;    # DMP disabled
mvm -p myclass.class; # DMP enabled
```

- Minimize performance penalty when disabled
- Allow object- or thread-specific behavior
- Compile DMP code out of virtual machine

```
./configure --enable-dmp=no && make && sudo make install;
mvm -p myclass.class;      # -p = DMP enabled
Invalid switch option 'p'
```

Design

- Global `dmp` module.
- DMP-specific modules for `object`, `thread`, `nlock` (object monitor) and `table`.

Global dmp module

- Maintain thread set in creation order

```
int dmp_add_thread(struct dmp *d, int r);    /* called when Thread.start() begins */
int dmp_remove_thread(struct dmp *d, int r); /* called when Thread.run() terminates */
```

- Control thread execution
  - Block threads at end their serial/parallel segment
  - Wake each thread in creation order during serial mode

```
int dmp_thread_block(struct dmp *d, struct thread_dmp *td); /* called by thread at end of segment */
```

- Implements default ownership table policy
  - Indicate if thread can proceed immediately with load/store or must block until serial mode
  - Indicate if ownership of object should be changed and how

```
/* takes current owner ID accessing thread ID
 * returns thread action (proceed/block) and owner action (shared/private/none)
 */
int dmp_shm_read(struct dmp *d, int c, int r, enum dmp_thread_action *ta, enum dmp_owner_action *oa);
int dmp_shm_write(struct dmp *d, int c, int r, enum dmp_thread_action *ta, enum dmp_owner_action *oa);
```

DMP-specific modules

- `object`, `thread`, `table` and `nlock` instances store pointer to DMP-specific module instance

```
int object_create(struct class *c, uint32_t n, struct object **o) {
#ifdef DMP
        if (dmp == NULL)
                object->dmp = NULL;
        else
                object->dmp = dmp_create_object_dmp(dmp, object);
#endif
}
```

- Without DMP, performance penalty is `dmp` pointer field and extra pointer comparisons

```
int object_load_field(struct object *o, int i) {
#ifdef DMP
        if (o->dmp != NULL)
                object_dmp_load(o->dmp, i);
#endif

        return o->fields[i];
}
```

DMP-specific modules cont'd.

- Each instance given an attributes record
- Attributes contain operations table implementing DMP operations for that module
- Attributes could be made object- or thread-specific

Object DMP

- Detect communicating `getfield` / `putfield` instructions
- Proceed or block thread and change `owner` attribute after consulting `dmp_shm_read` / `dmp_shm_write`

```
struct object_dmp_ops {
        int  (*load)(struct object_dmp *od, int i);        /* called inside getfield */
        int (*store)(struct object_dmp *od, int i, int r); /* called inside putfield */
        int (*chown)(struct object_dmp *od, int n);        /* change object owner */
};

struct object_dmp_attr {
        int owner;              /* current owner ID, 0 == shared */
        int depth;              /* ownership depth used by chown() */
        struct object_dmp_ops *ops;
};
```

Thread DMP

- Handle thread creation/destruction
- Add/remove `thread` from `dmp` module with `dmp_add_thread` / `dmp_remove_thread`
- Increment `thread` quantum instruction counter, block with `dmp_thread_block` when quantum in finished
- Use non-blocking `join` / `sleep` implementations

```
struct thread_dmp_ops {
        int  (*thread_creation)(struct thread_dmp *td);                 /* called in Thread.start() */
        int  (*thread_start)(struct thread_dmp *td);                    /* called at top of Thread.run(
) */
        int  (*thread_destruction)(struct thread_dmp *td);              /* called at bottom of Thread.r
un() */
        int  (*thread_join)(struct thread_dmp *td);                     /* called in Thread.join() */
        int  (*thread_sleep)(struct thread_dmp *td, int32_t m);         /* called in Thread.sleep() */
        int  (*execute_instruction)(struct thread_dmp *td, uint32_t o); /* called in fetch/execute cycl
e */
};

struct thread_dmp_attr {
        enum thread_dmp_serial_mode serial_mode; /* full/reduced serial mode */
        int lock_count;                          /* # of acquired locks, 0 == end serial segment */
        int quantum_size;                        /* instructions per quantum */
        uint64_t instruction_counter;            /* instructions executed in current quantum */
        struct thread_dmp_ops *ops;
};
```

NLock DMP (Object Monitors)

- Use non-blocking versions of `pthread_mutex_t` functions
- Increment/decrement DMP-specific `thread` module's lock count

```
struct nlock_dmp_ops {
        int  (*lock)(struct nlock_dmp *nd);   /* called in monitorenter */
        int  (*unlock)(struct nlock_dmp *nd); /* called in monitorexit */
};

struct nlock_dmp_attr {
        struct nlock_dmp_ops *ops;
};
```

Table DMP

- Hash table implemented natively inside virtual machine
- Table key/values must be guarded as if they were actual Object fields

```
struct table_dmp_ops {
        int  (*load)(struct table_dmp *td); /* load table field */
        int (*store)(struct table_dmp *td); /* store table field */
};

struct table_dmp_attr {
        struct table_dmp_ops *ops;
};
```

DMP Statistics

Garbage Collection

- Determining when a collection cycle will occur is not deterministic
- Serial collector only, run at end of serial mode when heap is using `90%` or more of its available memory.

Results

Racey

- Deterministic stress test
- Ran 10,000 times for each configuration

Benchmarks

- Parallel radix sort - Multithreaded radix sort of 500 random 16-bit integers
- Jacobi - uses the Jacobi method to simulate temperature changes on a 20x25 plate
- Parallel DPLL - Multithreaded boolean satisfiability using the DPLL algorithm

Parameters

- threads - 2, 4, 8 or 16 threads
- quantum size - 1000, 10000, and 100000 instructions
- full serial mode or reduced serial mode
- ownership table granularity - 1, 5 and 10 depth

Evaluation

- overhead - measure difference in execution time when compared to a non-DMP virtual machine
- measure difference in performance when parameters are changed

Each benchmark was run 10 times for each combination of parameters. Run-times are averages.

Radix

- No synchronized blocks in implementation, threads operate on disjoint indexes of shared table
- Average overhead 54% - 4,520%
- Fastest DMP run 2.65 seconds, fastest non-DMP run 1.27 seconds
- Not sensitive to choice of serial mode
- Larger ownership depth results in worse execution times, likely due to cost of rewriting ownership of all entries in shared table

Jacobi

- Number of threads fixed at 20
- Average overhead 27% - 1,117%
- Fastest DMP run 3.71 seconds, fastest non-DMP run 2.92 seconds
- Calculates temperature change of plate using two shared tables
- Clear advantage to using reduced serial mode
  - 3.71 / 16.00 seconds execution time
  - 1,842 vs. 17,616 blocking reads/writes
  - 175 vs. 3,081 rounds

```
class Worker extends Thread {
        Object run() {
                for (i = 0;  i < columns;  i = i + 1) {
                        synchronized (oldp)
                                oldp.get(...);             // get old temperature
                        synchronized (newp)
                                tmp = newp.put(...);       // calculate new temperatue
                        synchronized (oldp)
                                change = oldp.get() - tmp; // calculate temperature change
                }
        }
}
```

Parallel DPLL

- Threads traverse tree of possible `true` / `false` permutations for the problem variables, stealing from other threads when they run out of work.
- Average overhead -23% to 2,789%
- Fastest DMP run .95 seconds, fastest non-DMP run 0.71 seconds
- Showcases ineffiency of maTe virtual machine
- Some DMP runs beat non-DMP runs by a small margin
- Not sensitive to ownership table depth for 2/4 threads, but 8/16 show extreme jumps:
  - 8 threads - 11.47 vs. 21.75 seconds
  - 16 threads - 21.29 vs. 176.84 seconds

Conclusions

- **Results:** Average slowdown of 19% - 2800%
- Results do not back up thesis
- Overhead may still be acceptable for debugging
- There are still advantages
  - No recompiling
  - Quickly tweak DMP parameters with command-line arguments
- Implementing efficient multithreaded virtual machine is difficult
- Poor multithreaded performance, did not scale

Future Work

- Adaptive ownership table policy
- Source code annotations/static analysis optimizations
- Improve multithreaded performance
- Optimize maTe compiler
- Longer-running benchmarks
- Implement DMP in real Java virtual machine

Questions?