Deterministic Parallel Random-Number Generation for Task-Parallel* Platforms (2012)

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*Paper refers to Task-Parallel as Dynamic Threading which is no longer in popular use

Why do we want determinism in programs?

- Debuggability
  - Determinism makes it easy to replicate situations in which the bug occurs
  - Allows experiments to be performed to determine what mismatches the expected result
- What does determinism mean in practice?
  - Typically, that the program’s execution is equivalent in behavior to the serial execution of a program

Why use a Task-Parallel Platform like Cilk?

- Parallelism is a desired feature which introduces non-determinism
- Task-Parallel Platforms are able to control and manage this non-determinism through their schedulers
- Contrasts with Static/POSIX Threads which are common but require the programmer to explicitly manage scheduling and load balancing

Mitigating RNG Non-determinism

- RNG is made deterministic through a seed which is its initial state 0
- RNG on each request to generate a new number enters a new state, i.e. state 0 goes to state 1
- However, parallelism complicates things, suddenly execution ordering can impact the ordering of RNG requests, thereby making a simple seed approach ineffective

Global RNG - Potential Solution #1

- Share a single RNG between all threads through a lock
- Lots of contention on lock and so is not very performant
- The state the RNG is in when a thread issues a request is dependent on the execution order of all threads

Worker-local RNG - Potential Solution #2

- No lock needed since each worker has their own RNG
  - This solves the contention issue
- However, it cannot guarantee same RNG call goes to the same worker every time the program is run because of the non-deterministic scheduler
- Problem of these two solutions is that the RNG seed is based on the previous state, which is dependent on execution order
- How to create a solution based on some globally fixed ID?

Outline

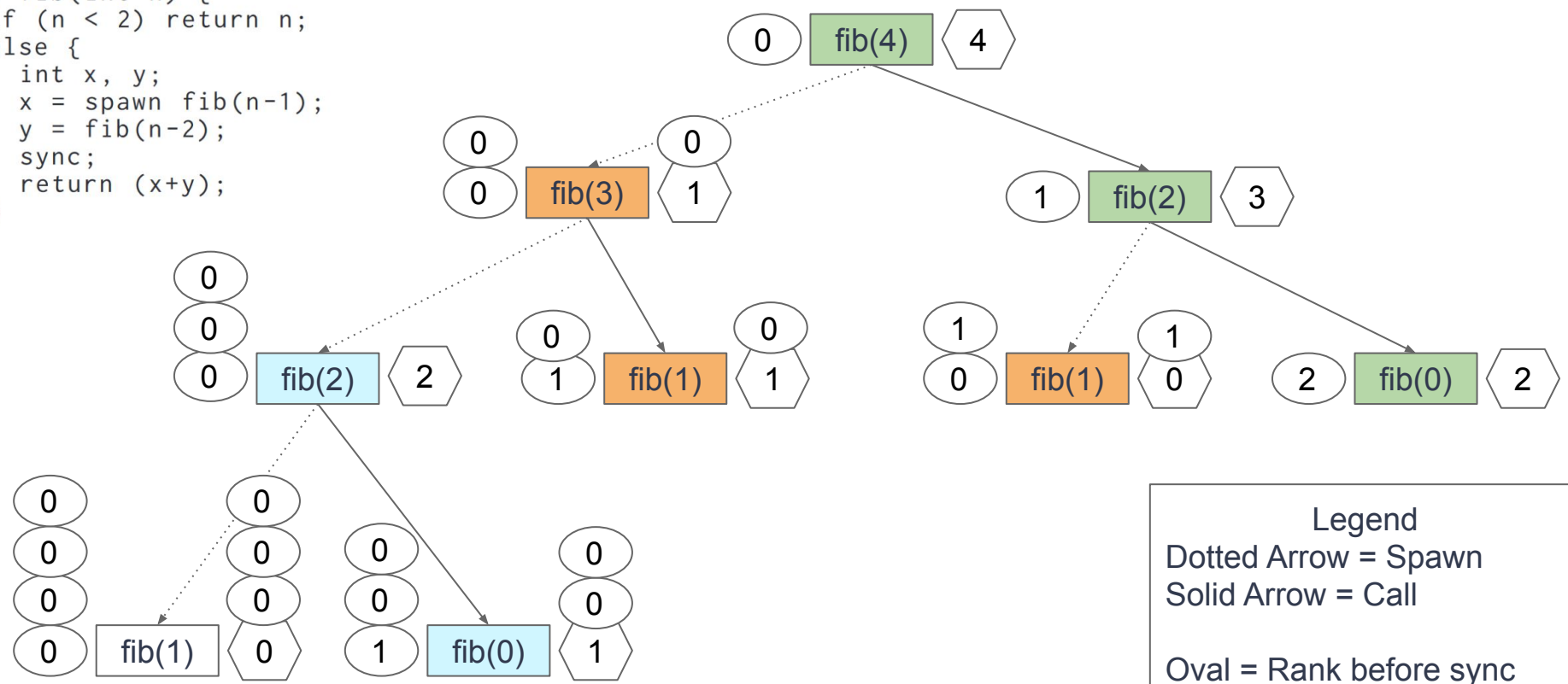
1. Pedigrees
   - The Solution
2. Dot-Mix
   - Pedigree Based DPRNG*
3. Results
4. Conclusion

*Deterministic Parallel Random Number Generator

What are Pedigrees and How Can They Help?

- Uniquely identifies function on 2 key factors
  - What function spawned it? (Its parent)
  - How many functions did its parent spawn before it? (Its rank)
- This is scheduler independent

```
int fib(int n) {
  if (n < 2) return n;
  else {
    int x, y;
    x = spawn fib(n-1);
    y = fib(n-2);
    sync;
    return (x+y);
  }
}
```



Spawn Tree of Recursive Parallel Fibonacci

DOT-Mix

- Pedigrees are variable length and the random numbers must fit into a fixed sized machine word
- We can’t directly use pedigrees to generate random numbers
- Use compression function that takes the pedigree and takes a dot product with random numbers to generate a word sized number

RC6 Block Cipher - The Mix in DOT-Mix

- The compression is not enough, highly correlated pedigrees will result in highly correlated numbers generated
- We need a mixing function, the one in DOT-Mix is as such:
- First, swap top and bottom half of bits of compressed value
- Then, apply function *f* to compressed value *z* for *r* rounds
  - Higher rounds creates greater overhead but better RNG

$$f(z) = \phi(2z^2 + z) \bmod m\ .$$

Results of RNG Quality

- Comparable to Mersenne Twister in Dieharder RNG benchmark
- Optimal choice of r = 4

Test	*r*	*Passed*	*Weak*	*Poor*	*Failed*
Mersenne twister	–	79	7	7	14
DotMix (tree)	16	83	6	4	14
	8	84	6	4	13
	4	81	5	7	14
	2	81	5	5	16
	1	3	2	3	99
	0	0	0	0	107
DotMix (loop)	16	82	2	8	15
	8	79	6	8	14
	4	79	5	8	15
	2	79	4	8	16
	1	55	2	8	42
	0	2	0	1	104
LCGMix (tree)	4	84	4	6	13
	0	24	6	21	56

Results of Performance Overhead

- Adding Pedigrees to Cilk less than 1% overhead on real world applications
- DOT-Mix within reasonable range of overhead for debugging programs

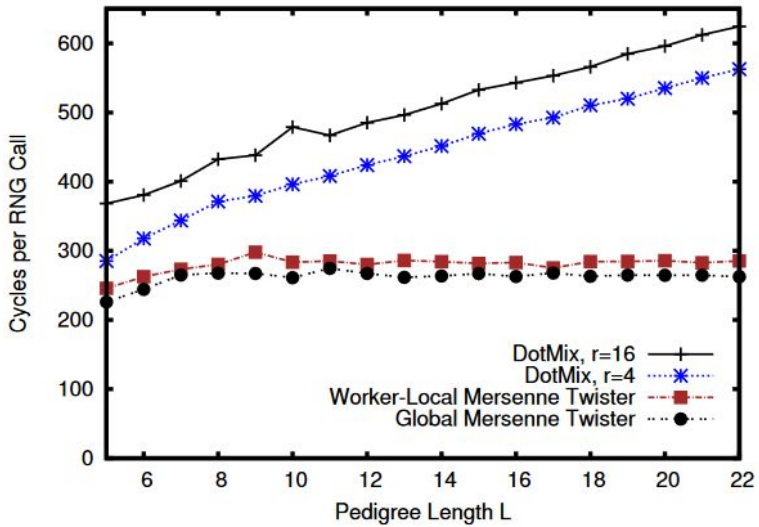


Figure 8: Overhead of various RNG's on the CBT benchmark when generating $n = 2^{20}$ random numbers. Each data point represents the minimum of 20 runs. The global Mersenne twister RNG from the GSL library [21] only works for serial code, while the worker-local Mersenne twister is a nondeterministic parallel implementation.

Conclusion + Future Work

- Extending 4-independent hash functions to Pedigrees
  - While unlikely, if a collision occurs, it is much more likely for DOT-Mix to produce many subsequent collisions

- Applications where pedigree memoization with incremental hash functions are performant