

Performance Considerations in Multi-Threaded Programs

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Upfront Note

Correctness cannot be traded for performance. No one cares about the performance of code that contains data races, atomicity violations, ordering violations, or is prone to deadlocks.

- That said, let's examine the cost of locking in particular
- Indirect cost (resulting in loss of performance due to the use of locking)
 - Simulated on following slides 5 CPU-bound processes contending for L locks, holding each lock for duration D , then running for duration U without lock. Thread chooses lock randomly.
 - Lightgreen are threads running without holding locks
 - Other colors are threads holding locks
- Direct cost (involved in actions the system had to take to implement it)

Indirect Cost: Loss of Parallelism Due To Single Lock



Figure 1: Fixed:
 $U=2/D=2/L=1/40.8\%$



Figure 2: Fixed:
 $U=18/D=2/L=1/96\%$



Figure 3: Poisson:
 $U=2/D=2/L=1/41.6\%$



Figure 4: Poisson
 $U=18/D=2/L=1/94.4\%$



Indirect Cost: Loss of Parallelism with 2 Locks

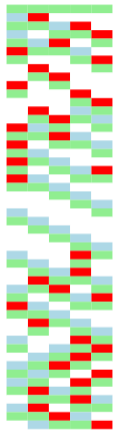


Figure 5: Fixed:
 $U=2/D=2/L=2/65.2\%$

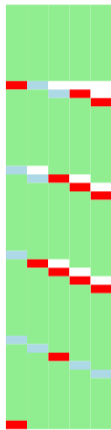


Figure 6: Fixed:
 $U=18/D=2/L=2/96\%$

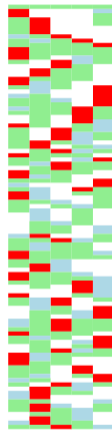


Figure 7: Poisson:
 $U=2/D=2/L=2/72.2\%$



Figure 8: Poisson
 $U=18/D=2/L=2/99.4\%$



Indirect Cost: Loss of Parallelism with 4 locks

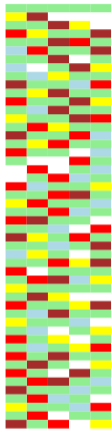


Figure 9: Fixed:
 $U=2/D=2/L=4/89.6\%$



Figure 10: Fixed:
 $U=18/D=2/L=4/98\%$

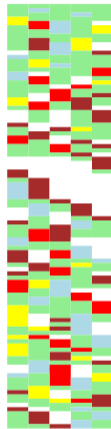


Figure 11: Poisson:
 $U=2/D=2/L=4/79.2\%$



Figure 12: Poisson
 $U=18/D=2/L=4/99.4\%$
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Indirect Cost: Loss of Parallelism

- Serialization due to locks diminishes CPU utilization and increases an individual task's latency
 - For parallel, mostly CPU-bound applications this translates directly into loss of speedup
 - Particularly if locks are contended (situation where threads are blocked on a lock arises frequently)
 - Particularly/assuming if there's nothing else to run during times when threads are blocked
- This serialization effect would be exacerbated if blocked threads held locks (e.g., I/O, sleep, sem_wait, pthread_join?)
- Rule: Critical sections should not call any functions that may block, or else the critical section may become inaccessible

```
pthread_mutex_lock(&shutdownLock);  
pthread_mutex_lock(&infoLock);  
while (!moreInformation)  
    pthread_cond_wait(&moreInfo, &infoLock);  
pthread_mutex_unlock(&infoLock);  
pthread_mutex_unlock(&shutdownLock);
```

```
pthread_mutex_lock(&lock);  
read(fd, buf, sizeof buf);  
pthread_mutex_unlock(&lock);
```

Solution: Breaking Up Locks

- Cautionary side note: several large software systems were either never parallelized or started with a “big lock” approach: the Linux kernel, Python’s GIL, gtk GUI lock
- Idea: instead of having lock L protect data (A, B, C) introduce locks L_A, L_B, L_C to protect $A, B,$ and $C,$ respectively.
- Thus, updates to A will not prevent simultaneous updates to B
- This introduces 3 risks
 - 1 Higher risk of atomicity violations: if A and B must be updated in tandem (atomically) - say update to B is dependent on A having a value, both locks must be held. Always holding both locks negates purpose of having 2 locks; not holding them both where needed leads to atomicity violations
 - 2 Higher risk of deadlocks: if there are situations where both locks must be held, a locking order must be established to avoid deadlocks
 - 3 More frequent calls to lock/unlock translates to increased direct cost (locking overhead)

Direct Cost of Locking

- What happens under the hood in a call to `pthread_mutex_lock()`?
 - Fast path: an atomic instruction tries to acquire the lock (if available) without causing a mode switch (e.g. `cmpxchg %rax, (%rbx)`) - in memory flag that indicates if lock is available
 - For fast path numbers, see Jeff Dean/Peter Norvig/Colin Scott Numbers Every Programmer Should Know: $17\times$ L1 reference, $4\times$ L2 reference, $\frac{1}{6}\times$ main memory reference (17ns as of 2010's)
 - Slow path: if atomic instruction indicates that lock is already held, make system call (`futex_wait`) and inform kernel that thread should block. Then, context switch to other ready thread (if any)
- ... `pthread_mutex_unlock()`?
 - Fast path: just place lock into unlocked state
 - Slow path (someone is waiting for the lock): make system call (`futex_wakeup`) and inform kernel to wake up any waiting thread(s). These threads are unblocked (made ready), placed into ready queue, and eventually scheduled - another context switch
- Both mode and context switches can be costly (e.g. pipeline stalls, cache pollution)

Conclusion

- Optimizing locking is difficult
- Correctness is paramount
- Performance impact can be difficult to predict
- Strategies to reduce serialization may increase locking overhead
- General approach should be start conservatively with coarse-grained locking strategies, and move to finer-grained locking as part of an iterative optimization process