Early Experiences on Accelerating Dijkstra’s Algorithm Using Transactional Memory

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Outline

1. Dijkstra’s Basics
2. Straightforward Parallelization Scheme
3. Helper-Threading Scheme
4. Experimental Evaluation
5. Conclusions
The Basics of Dijkstra’s Algorithm

SSSP Problem

- Directed graph $G = (V, E)$, weight function $w : E \rightarrow \mathbb{R}^+$, source vertex $s$
- $\forall v \in V : \text{compute } \delta(v) = \min\{w(p) : s \xleftrightarrow{p} v\}$

Shortest path estimate $d(v)$

- gradually converges to $\delta(v)$ through relaxations
- $\text{relax } (v, w) : d(w) = \min\{d(w), d(v) + w(v, w)\}$
  - can we find a better path $s \xleftrightarrow{p} w$ by going through $v$?

Three partitions of vertices

- Settled: $d(v) = \delta(v)$
- Queued: $d(v) > \delta(v)$ and $d(v) \neq \infty$
- Unreached: $d(v) = \infty$
The Basics of Dijkstra’s Algorithm

Serial algorithm

1. **Input**: $G = (V, E)$, $w : E \rightarrow \mathbb{R}^+$, source vertex $s$, min $Q$
2. **Output**: shortest distance array $d$, predecessor array $\pi$
3. **foreach** $v \in V$ **do**
   4. $d[v] \leftarrow \text{INF}$;
   5. $\pi[v] \leftarrow \text{NIL}$;
   6. Insert($Q$, $v$);
4. **end**
5. $d[s] \leftarrow 0$;
6. **while** $Q \neq \emptyset$ **do**
7.   $u \leftarrow \text{ExtractMin}(Q)$;
8.   **foreach** $v$ adjacent to $u$ **do**
9.       $\text{sum} \leftarrow d[u] + w(u, v)$;
10.      **if** $d[v] > \text{sum}$ **then**
11.         DecreaseKey($Q$, $v$, $\text{sum}$);
12.         $d[v] \leftarrow \text{sum}$;
13.         $\pi[v] \leftarrow u$;
14.      **end**
8. **end**
The Basics of Dijkstra’s Algorithm

Min-priority queue implemented as binary min-heap

- maintains all but the settled vertices
- min-heap property: \( \forall i : d(\text{parent}(i)) \leq d(i) \)
- amortizes the cost of multiple ExtractMin’s and DecreaseKey’s
  - \( O((|E| + |V|)\log|V|) \) time complexity
Straightforward Parallelization

Fine-grain parallelization at the inner loop level

 Fine-Grain Multi-Threaded

```c
/* Initialization phase same to the serial code */
while Q \neq \emptyset do
    Barrier
    if tid = 0 then
        u <- ExtractMin(Q);
    Barrier
    for v adjacent to u in parallel do
        sum <- d[u] + w(u, v);
        if d[v] > sum then
            Begin-Atomic
            DecreaseKey(Q, v, sum);
            End-Atomic
            d[v] <- sum;
            \pi[v] <- u;
    end
end
```

Issues:
- speedup bounded by average out-degree
- concurrent heap updates due to DecreaseKey's
- barrier synchronization overhead
Concurrent Heap Updates with Locks

- **Coarse-grain synchronization** (*cgs-lock*)
  - enforces atomicity at the level of a `DecreaseKey` operation
  - one lock for the entire heap
  - serializes `DecreaseKey`'s

- **Fine-grain synchronization** (*fgs-lock*)
  - enforces atomicity at the level of a single swap
  - allows multiple swap sequences to execute in parallel as long as they are *temporally* non-overlapping
  - separate locks for each parent-child pair
Performance of FGMT with Locks

Software barriers dominate total execution time
- 72% with 2 threads, 88% with 8
- replace with idealized (simulated) zero-latency barriers

Fgs-lock scheme more scalable, but still fails to outperform serial
- locking overhead (2 locks + 2 unlocks per swap)
Concurrent Heap Updates with TM

TM-based
- **Coarse-grain synchronization (cgs-tm)**
  - enclose `DecreaseKey` within a transaction
  - allows multiple swap sequences to execute in parallel as long as they are *spatially* (and temporally) non-overlapping
  - conflicting transaction stalls and retries or aborts
- **Fine-grain synchronization (fgs-tm)**
  - enclose each swap operation within a transaction
  - atomicity as in *fgs-lock*
  - shorter but more transactions
TM-based schemes offer speedup up to $\sim 1.1$

- less overhead for $cgs-tm$, yet equally able to exploit available concurrency
Helper-Threading Scheme

Motivation
- expose more parallelism to each thread
- eliminate costly barrier synchronization

Rationale
- in serial, relaxations are performed only from the extracted (settled) vertex
- allow relaxations for out-edges of queued vertices, hoping that some of them might already be settled
  - main thread operates as in the serial algorithm
  - assign the next $t$ vertices in the queue ($x_2 \ldots x_{t+1}$) to $t$ helper threads
  - helper thread $k$ relaxes all out-edges of vertex $x_k$
- speculation on the status of $d(x_k)$
  - if already optimal, main thread will be offloaded
  - if not optimal, any suboptimal relaxations will be corrected eventually by main thread
the main thread stops all helpers at the end of each iteration

unfinished work will be corrected, as with mis-speculated distances
for a single neighbour, the check for relaxation, updates to the heap, and updates to $d, \pi$ arrays, are enclosed within a transaction

- performed “all-or-none”
- on a conflict, only one thread commits

interruption of helper threads implemented through TM, as well
Helper-Threading Scheme

### Main thread

```
while Q \neq \emptyset do
    u ← ExtractMin(Q);
    done ← 0;
    foreach v adjacent to u do
        sum ← d[u] + w(u, v);
        Begin-Xact
        if d[v] > sum then
            DecreaseKey(Q, v, sum);
            d[v] ← sum;
            \pi[v] ← u;
        End-Xact
    done ← 1;
End-Xact
```

```
Why with TM?
- composable
  - all dependent atomic sub-operations composed into a large atomic operation, without limiting concurrency
- optimistic
- easily programmable
```

### Helper thread

```
while Q \neq \emptyset do
    while done = 1 do;
    x ← ReadMin(Q, tid)
    stop ← 0
    foreach y adjacent to x and while stop = 0 do
        Begin-Xact
        if done = 0 then
            sum ← d[x] + w(x, y)
            if d[y] > sum then
                DecreaseKey(Q, y, sum)
                d[y] ← sum
                \pi[y] ← x
            else
                stop ← 1
        End-Xact
    done ← 1;
End-Xact
```
Experimental Setup

Full-system simulation
- Simics 3.0.31 in conjunction with GEMS toolset 2.1
- boots unmodified Solaris 10 (UltraSPARC III Cu)

LogTM ("Signature Edition")
- eager version management
- eager conflict detection
  - on a conflict, a transaction stalls and either retries or aborts
- HYBRID conflict resolution policy
  - favors older transactions

Hardware platform
- single CMP system (configurations up to 32 cores)
- private L1 caches (64KB), shared L2 cache (2MB)

Software
- Pthreads for threading and synchronization
- Simics “magic” instructions to simulate idealized barriers
- Sun Studio 12 C compiler (-xO3)
Graphs

Three graph families

- **Random**: $G(n, m)$ model
- **SSCA#2**: cliques with varying size $(1 - C)$ connected with probability $P$
- **R-MAT**: power-law degree distributions

GTgraph graph generator

Fixed #nodes (10K), varying density

- sparse ($\sim$10K edges)
- medium ($\sim$100K edges)
- dense ($\sim$200K edges)
Helper-Threading
- speedups in 6 out of 9 cases (not all shown), up to 1.46
- performance improves with increasing density
- main thread not obstructed by helpers (<1% abort rate in all cases)

FGMT with TM
- speedups only with perfect barriers
- optimistic parallelism does exist in concurrent queue updates
Conclusions

FGMT

- conventional synchronization mechanisms incur unacceptable overhead
- TM reduces overheads and highlights the existence of parallelism, but still requires very efficient barriers to offer some speedup

HT with TM

- exposes more parallelism and eliminates barrier synchronization
- noteworthy speedups with minimal code extensions

Future work

- more aggressive parallelization schemes
- dynamic adaptation of helper threads to algorithm’s execution phases
- explore impact of TM characteristics
- applicability of HT on other SSSP algorithms (Δ-stepping, Bellman-Ford) and other similar ("greedy") applications
Thank you!

Questions?