A Distributed Deadlock Detection and Resolution Algorithm for Process Networks

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Motivation

- DSP systems are growing in size and complexity
- Parallel & distributed implementations are necessary
- **Problem**: Effective parallel programming is difficult
  - Non-determinate execution
  - Hard to predict and prevent deadlock
  - Difficult to make scalable software (e.g. rendezvous models)
- Current approaches typically lack formal underpinnings
Process Networks (PN)

- **Solution**: Process Networks, a formal model \([\text{Kahn 74}]\)
- Mathematically provable properties
  - Guarantees determinate execution
  - Allows concurrent execution
- A dataflow model
  - Each **node** represents a computational unit
  - Each **edge** represents a one-way FIFO queue
- Naturally models parallelism in a DSP system
- Extremely scalable with simple, local scheduling rules
**Bounded Scheduling of PN**

- Kahn’s original PN assumes infinite memory!
- **Clever dynamic scheduling of the nodes allows execution in bounded memory, if it is possible** [Parks 95]
  - May introduce *artificial deadlocks* due to queue bounds
  - Dynamic deadlock detection & resolution required
  - Lengthen shortest deadlocked full queue to resolve

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Parks ‘95</th>
<th>Geilen &amp; Basten ‘03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadlock detector</td>
<td>Global deadlocks</td>
<td>Local deadlocks</td>
</tr>
<tr>
<td>Preserves PN properties</td>
<td>No (counterexamples)</td>
<td>Yes, if an effective PN</td>
</tr>
</tbody>
</table>

- Deadlock detection algorithms were not provided
Bounded Scheduling of PN

- Existing distributed algorithm [Mitchell & Merritt 84] can detect presence of deadlocks in a PN [Olson & Evans 05]
- We present an algorithm to detect and resolve artificial deadlocks for bounded scheduling of PN
- D4R algorithm: Distributed Dynamic Deadlock Detection and Resolution algorithm
  - Determines whether a deadlock is real or artificial
  - For artificial deadlocks, notifies node which is blocked on culpable queue that must grow for resolution
  - Distributed and scalable (good for distributed PN)
Mitchell & Merritt Algorithm [1984]

- Originally for distributed database applications
- A single resource algorithm -- a process waits only on a single other process (also true with PN)
- Each process contains algorithm state variables
- Transactions between interacting (waiting) processes construct a wait-for dependency graph
- A dependency cycle indicates a deadlock, which is detected by lowest priority process in the cycle
- Proofs for correctness provided

Our D4R algorithm borrows heavily from M&M
D4R State Variables

- Each process contains public and private triples of D4R algorithm state information:
  - `count`, a non-decreasing counter
  - `nodeID`, a unique node identifier
  - `q_size`, size of queue upon which node is blocked
    - Set to -1 when blocking on read of an empty queue
    - Serves same function as M&M’s priority variable
    - Will identify the deadlock type and the culpable node
  - `count:nodeID` expresses concatenation (as in M&M)
**D4R State Transitions**

- **BLOCK**, a node blocks on a single other node
  - `count` is incremented, `q_size` set appropriately

- **TRANSMIT**, a node’s state travels upstream
  - If downstream state changes, it could propagate upward (minnn is minimum non-negative)

---

**STATE BEFORE**

```
<table>
<thead>
<tr>
<th>u</th>
<th>a</th>
<th>q</th>
</tr>
</thead>
</table>
```

- `outdegree=0`

**STATE AFTER**

```
<table>
<thead>
<tr>
<th>w</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>q</td>
<td>q</td>
</tr>
</tbody>
</table>
```

- `w=max(u,v)+1`

---

(u:a<v:b) or (u:a=v:b, q>r)

---

<table>
<thead>
<tr>
<th>public</th>
<th>count</th>
<th>private</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>nodeID</td>
<td>nodeID</td>
<td>q_size</td>
<td>q_size</td>
</tr>
</tbody>
</table>

---

p=minnn(r,s)

---
D4R State Transitions (2)

- **DETECT**, node’s state has circuited a *wait-for* cycle
  - If \( q_{\text{size}} < 0 \) then *real deadlock* -- a cycle of reads
  - Otherwise, blocked on queue that should grow

- **ACTIVATE**, resolve dependency and continue
  - Lengthen the queue to resolve *artificial deadlock*
Example: Resolution of an Artificial Deadlock

- A Bounded PN
- Initial conditions
  - All queues length 1
  - D4R states initialized
- Each node is an independent thread
- One of several possible orders of execution

Node B
while (true)
P.get(1)
R.put(1)

Node A
while (true)
Q.put(2)
P.put(1)

Node C
while (true)
R.get(1)
Q.get(2)

Q
P
R

0
0
0
0
0
0
0
0

- count
- count
- nodeID
- nodeID
- q_size
- q_size

public
private
count
count
nodeID
nodeID
q_size
q_size
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
4. A gets TRANSMIT from C
Example: Resolution of an Artificial Deadlock

- A BLOCKS on C
- B BLOCKS on A
- C BLOCKS on B
- A gets TRANSMIT from C
- B gets TRANSMIT from A
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
4. A gets TRANSMIT from C
5. B gets TRANSMIT from A
6. C gets TRANSMIT from B
Example: Resolution of an Artificial Deadlock

1. A \textit{BLOCKS} on C
2. B \textit{BLOCKS} on A
3. C \textit{BLOCKS} on B
4. A gets \textit{TRANSMIT} from C
5. B gets \textit{TRANSMIT} from A
6. C gets \textit{TRANSMIT} from B
7. A \textit{DETECTS} deadlock
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
4. A gets TRANSMIT from C
5. B gets TRANSMIT from A
6. C gets TRANSMIT from B
7. A DETECTS deadlock
8. A ACTIVATES to continue
   (Grow queue Q to 2)
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
4. A gets TRANSMIT from C
5. B gets TRANSMIT from A
6. C gets TRANSMIT from B
7. A DETECTS deadlock
8. A ACTIVATES to continue
9. B ACTIVATES to continue
   (dependency resolved)
Example: Resolution of an Artificial Deadlock

1. A BLOCKS on C
2. B BLOCKS on A
3. C BLOCKS on B
4. A gets TRANSMIT from C
5. B gets TRANSMIT from A
6. C gets TRANSMIT from B
7. A DETECTS deadlock
8. A ACTIVATES to continue
9. B ACTIVATES, continues
10. C ACTIVATES, continues
Comments

• Wait-for arcs coincide with the PN queues

• Larger counts and smaller q_sizes migrate along the wait-for graph in the opposite direction

• Exactly one node DETECTs a deadlock in N-1 to 2N-1 TRANSMIT steps (where N is number of nodes in cycle)

• Proofs provided in paper, based on [Mitchell & Merritt 84]

• Implementation provided as part of CPN library: http://www.ece.utexas.edu/~allen/CPN

• D4R algorithm performance is not a priority -- artificial deadlock is an exceptional condition
Conclusion

- Formal models like Process Networks can simplify development of complex, distributed DSP systems
- Execution in bounded memory requires dynamic deadlock detection and resolution
- Leveraged existing [Mitchell & Merritt 84] distributed algorithm for deadlock detection and resolution
- Provided a Distributed Dynamic Deadlock Detection and Resolution algorithm (D4R) to permit execution of PN in bounded memory
- Permits scalable implementation of bounded PN