Macrodebugging: Global Views of Distributed Program Execution

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Macroprogramming

- A single macroprogram $\rightarrow$ Several microprograms
- No support for debugging
- MacroLab
  - A macroprogramming framework that offers a vector programming abstraction similar to Matlab for Cyber-Physical Systems (CPSs).

MDB

- Like GDB
- “Macrodebugging” on a single machine
- Steps through a macroprogram in a sequential order
- Implemented for MacroLab

Example of MacroLab program

- Lines 1-4
  - Initializes
    - The motes vector of node IDs
    - The magSensors vector of magnetometer sensors
    - The magVals macrovector of magnetometer readings
    - neighborMag, n x n neighbor reflection vector
- Line 7
  - Reads from all magnetometer values
- Line 8
  - Creates an active vector with the IDs of all nodes that have at least 3 neighbors with values > THRESH

```
1  motes = RTS.getMotes('type ', 'tmote ')
2  magSensors =
       SensorVector(motes , 'magnetometer ')
3  magVals = Macrovector(motes)
4  neighborMag = neighborReflection(motes ,
       magVals)
5  THRESH = 500
6  every(1000)
7    magVals = magSensors .sense ()
8    active = find(sum(neighborMag >THRESH , 2)
       > 3)
9    maxNeighbor = max(neighborMag , 2)
10   leaders = find($\ldots$
11       maxNeighbor(active) == magVal(active))
12   focusCameras(leaders);
13 end
```

Example of MacroLab program (cont.)

- Line 9
  - Creates a maxNeighbor vector with the highest sensor value in neighborMag
- Line 10-11
  - Creates a leaders vector with the IDs of those nodes having the highest sensor value in an active neighborhood
- Line 12
  - Focus all available cameras on the leader nodes

```
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```
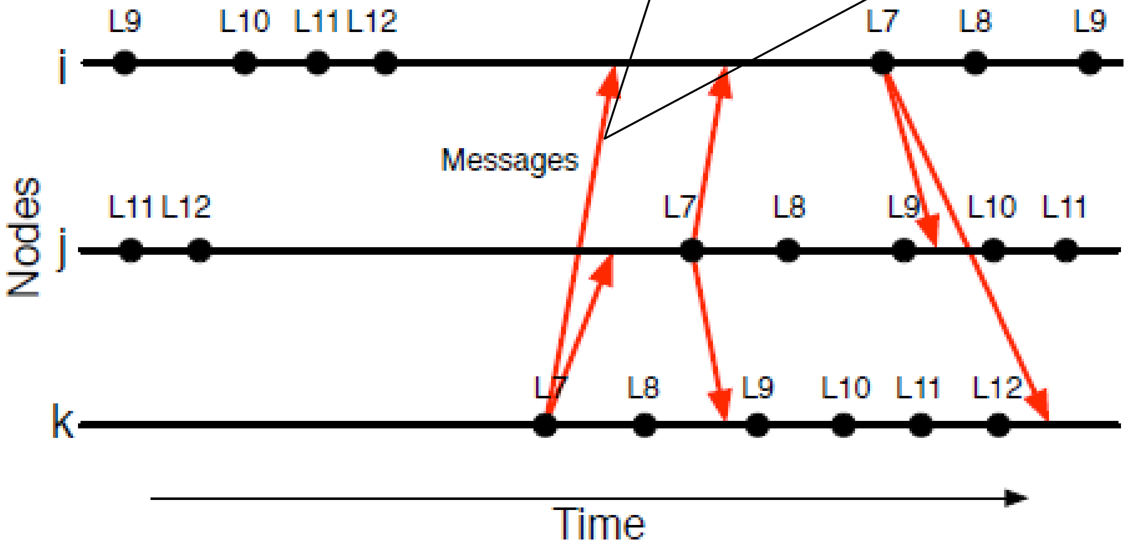

Example of MacroLab program (cont.)

- All nodes will execute the program asynchronously and independently

Magnetometer values automatically get reflected to neighboring nodes and populate the caches of neighborMag vector

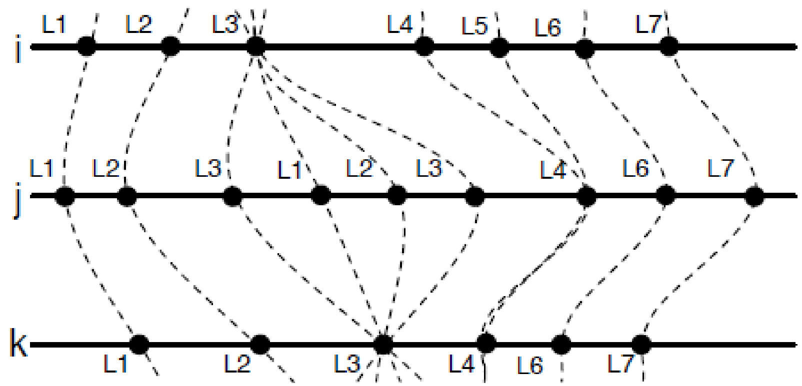


Three types of macroprogramming bugs

- Logical Error
  - active = **find**(**sum**(magVals>THRESH , 2) > 3)
- Configuration Error
  - Line 6, 1000ms might be too big
- Synchronization Error
  - Message loss, data races, asynchronous execution

MDB UI – Logically synchronous views

- Commands
  - lbreak(l)
    - Place a breakpoint at line l
  - lcont
    - Move forward to the next breakpoint
  - lstep[(l)]
    - Increment to the next line (or step l lines)
- Limitation
  - Views of distributed state may include values that correspond to different points in time



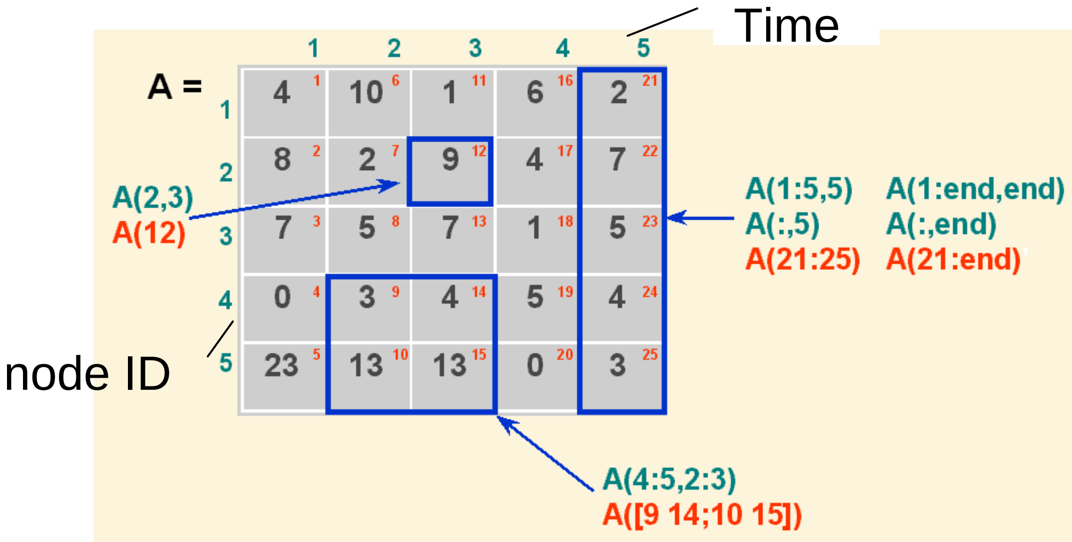

```
while( magVals < 10 )
  magVals = magSensor.sense()
end
if magVals > 3000
  magSensor.calibrate()
end
Display(magVals)
```

MDB UI – Temporally synchronous views

- Commands
  - tjump(t)
    - Change the state of the system to time t μs
  - tstep[(t)]
    - Change the state of the system to next logged time (or current time + t)
- Limitation
  - The user must be able to specify the exact times of interest

MDB UI – Historical Search

- Access the history of a macrovector by adding a new dimension to it
  - magVals(5, 1000)
- Standard Matlab operators can be applied to macrovectors
  - find(numel(leaders(:, :)) > 1)

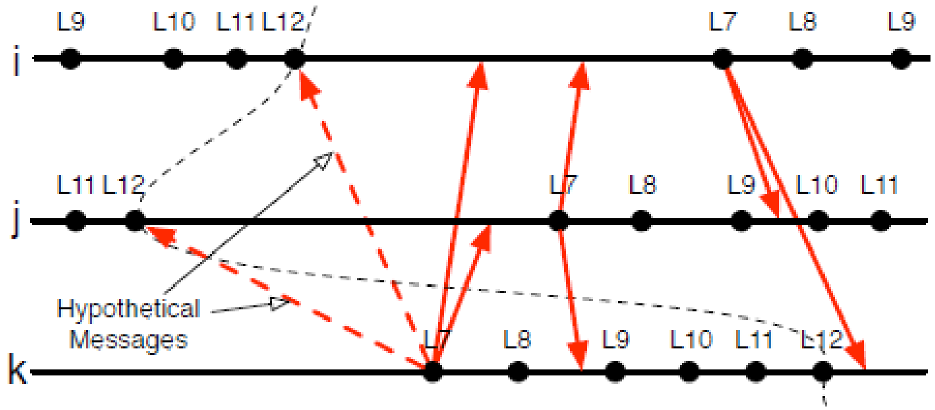


MDB UI – Hypothetical Changes

- Base timeline (bt)
  - The original execution trace that was collected during program execution
- Alternative timeline (at)
  - Generated by applying hypothetical changes to the base timeline
  - at = alt('magVals = 0', 7, bt)
- Four hypothetical changes

MDB UI – Hypothetical Barrier

- Barrier
  - A point in the source code that all nodes must reach before any node can proceed
- hb = alt('barrier()', 12, bt)
- message re-ordering

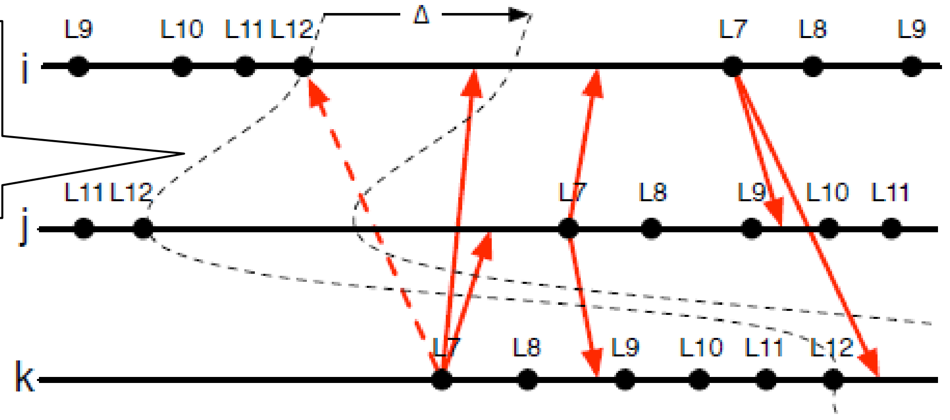


(a) Hypothetical Barrier

MDB UI – Hypothetical Time Delay

- Produces the distributed state that would have been produced if a time delay of Δt were inserted at a particular point in the macrocode
- dt = alt('deltat(10)',12, bt)
- message re-ordering

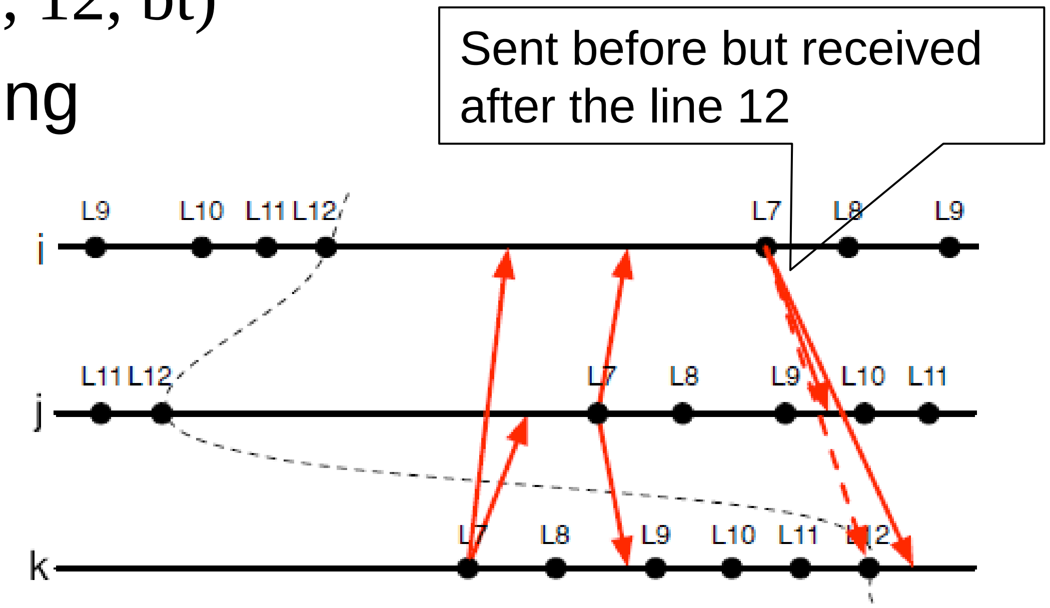
MDB first creates a logically synchronous view on line12



(b) Hypothetical Time Delay

MDB UI – Hypothetical Cache Coherence

- Shows the hypothetical distributed state if all caches were coherent at a give time
- cv = alt('coherent()', 12, bt)
- message re-ordering



(c) Hypothetical Cache Coherence

MDB UI – Hypothetical Cache Expiration

- Shows the hypothetical state that would result if cache expiration were used at a given line of code, without a particular expiration time
- ev = alt('expire(100000)', 12, bt)
  - ev stores the last values written to each element of the macrovector in the time interval
  - ev = NaN if an element had no value written to it within the time interval

MDB Execution Traces

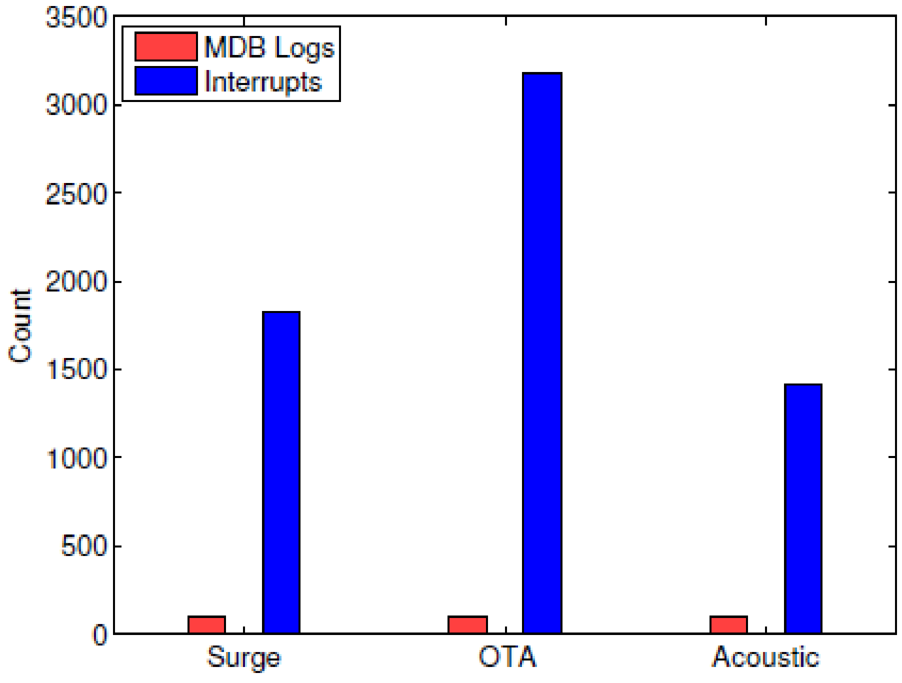
- Post-mortem debugger
  - Allow the user to inspect program execution after the logs are retrieved
- Data traces
  - Log entry
    - program counter, variable location, etc.
- RAM $\rightarrow$ external flash
  - Advantage
    - Reduces contention for the CPU
  - Disadvantage
    - Log entries in the RAM buffer may be lost if the node crashes

Distributed Timekeeping

- Causal consistency
  - Any event E that cause event E’ must have smaller timestamp than E
- Lamport algorithm
  - Any events on the sender have an earlier timestamp than events they might cause on the recevier
  - Used off-line after the logs are collected
- One Message every two minutes

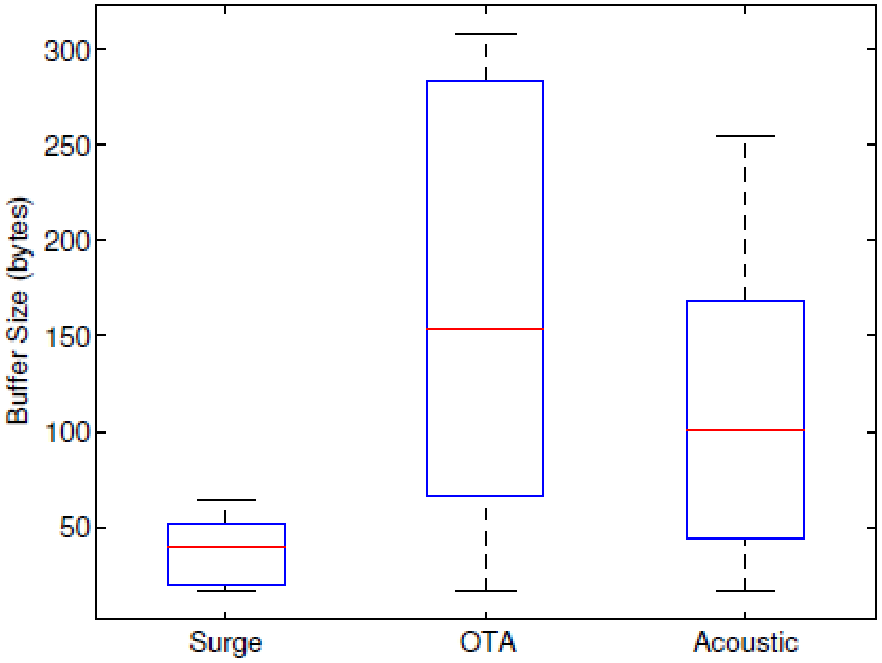
Data vs. Event Logging

- Data logging
  - Number of logging statement
- Event logging
  - Number of interrupts
- Testbed
  - 21 Tmote Sky nodes with photoresistor sensors



RAM overhead

- MDB has modest RAM requirements
- MDB needs to store a maximum of 304 bytes of data



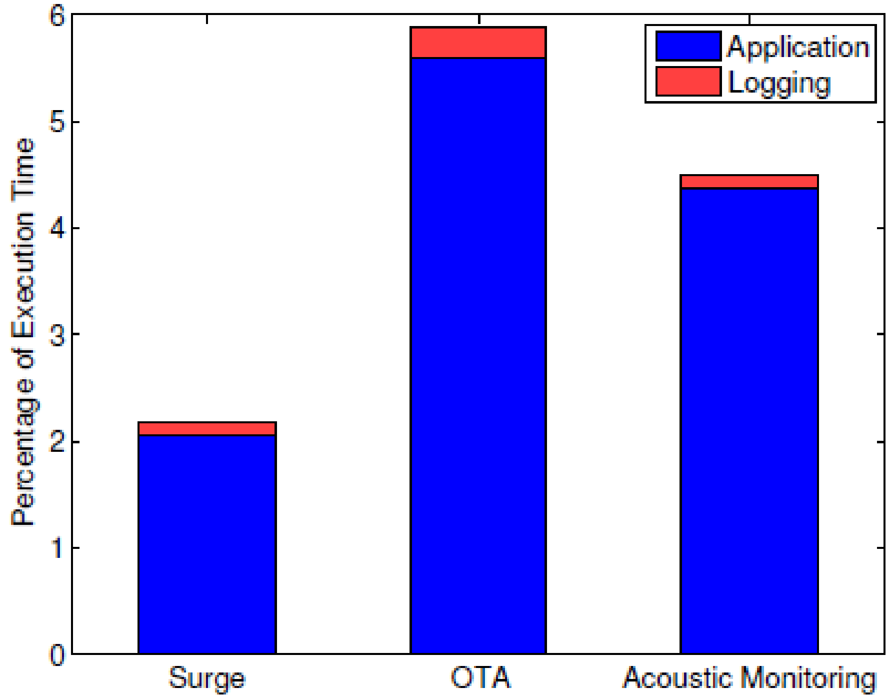
Flash overhead

- The applications store less than 300 Bps to the flash
- Tmote Sky has 1MB of external flash
- Approximately,
  - 9 hour logs for Surge

Application	Flash (Bps)	Wraparound (hr)
Surge	31	9
Accoustic	187	2
OTA	288	1

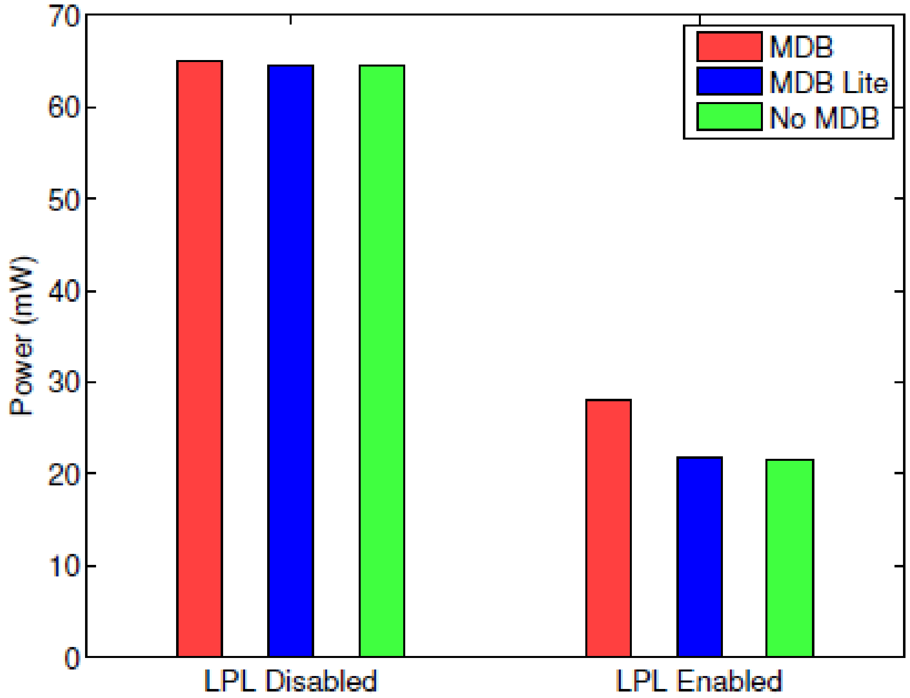
CPU overhead

- Count the logging instructions executed during a particular run
- Run the applications on Cooja simulator
  - 1 node for Surge
  - 5 nodes for Accoustic
  - 10 nodes for OTA
- Logging code executes for less than 0.5% of the total execution time



Energy Consumption

- Test application
  - OTA
- When Low-power listening (LPL) is enabled
  - With MDB
    - Consumes 30% more energy comparing to no-MDB
  - With MDB-lite
    - Consumes 0.9% more energy comparing to no-MDB



END

- Q&A