CS4021/4521 Advanced Computer Architecture II

Prof Jeremy Jones

Rm 4.16 top floor South Leinster St (SLS)

jones@scss.tcd.ie

South Leinster St

Timetable Slots

- Mon @ 5 Salmon
- Thurs @ 4 LB120
- Fri @ 3 LB08

use Fri @ 3 as a tutorial slot when needed

CONCURRENT PROGRAMMING WITH AND WITHOUT LOCKS

- mixture of theory and practice
- writing parallel programs (bucket sort, suffix array construction, binary search trees, …)

- Peterson and Bakery locks [locks without atomic instructions]
- Spin model checker [revision?]
- atomic instructions
- serialising instructions
- caches coherency and the cost of sharing data between CPUs
- lock implementations and their performance [TAS, TATAS, ticket, MCS,, …]

Concurrent Programming With and Without Locks

- lockless data structures and algorithms
  - CAS based
  - LIFOs, FIFOs, linked, lists, trees, hash tables, …
  - memory management [eg. hazard pointers]

- hardware transactional memory [HTM]
  - Herlihy and Moss [1993]
  - Intel Transactional Synchronisation Extensions (TSX)
  - hardware lock elision (HLE)
  - restricted transactional memory (RTM)

USEFUL BOOKS

- *The Art of Multiprocessor Programming*

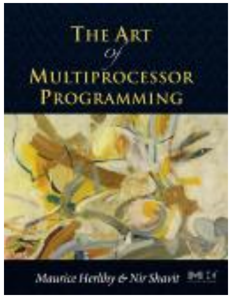
  Maurice Herlihy and Nir Shavit

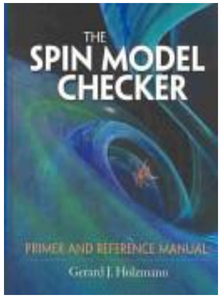
- *The Spin Model Checker: Primer and Reference Manual*

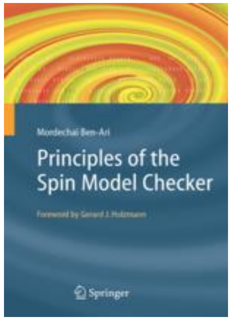
  Gerald J. Holzmann

- *Principles of the Spin Model Checker*

  Mordechai Ben-Ari







- Module website https://www.scss.tcd.ie/Jeremy.Jones/CS4021/CS4021.htm
  - lecture notes
  - coursework (3 or 4 exercises)
  - miscellaneous materials (papers, documentation, sample code, …)

ASSESSMENT [5 ECTS]

Coursework: 20%

- 3 or 4 coursework projects

Examination: 80%

- Dec 2018
- answer 3 out of 4 questions in 2 hours

MALBEC [malbec.scss.tcd.ie]

Supermicro 1U SuperServer 5018D-FNFT
Intel Xeon D-1540 2.0 GHz Broadwell CPU 45W
8 cores / 16 threads
128GB ECC RDIMM

Transactional Synchronization Extensions (TSX)
Haswell TSX implementation had a bug, Broadwell OK

Linux (Debian)

use for coursework

remote access via macneill or VPN

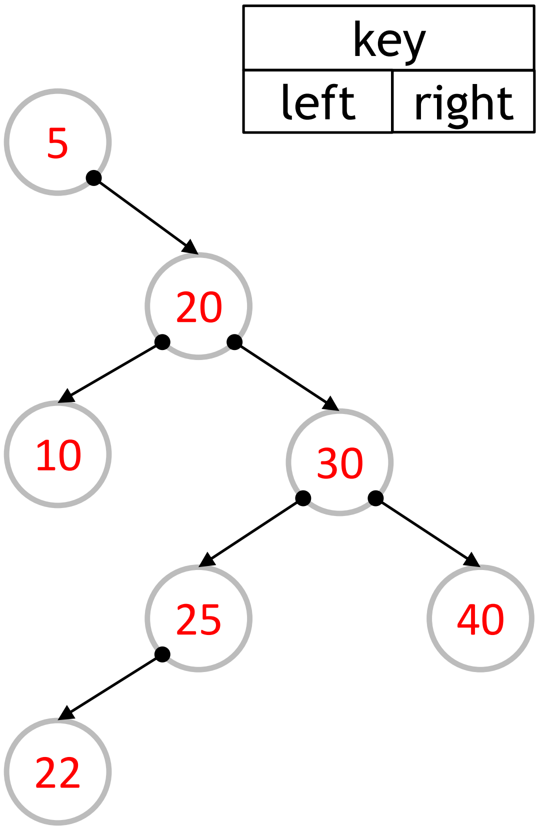
can use VS2017 “Linux development with C++” component to develop software remotely on malbec from a Windows PC

Why lockless algorithms?

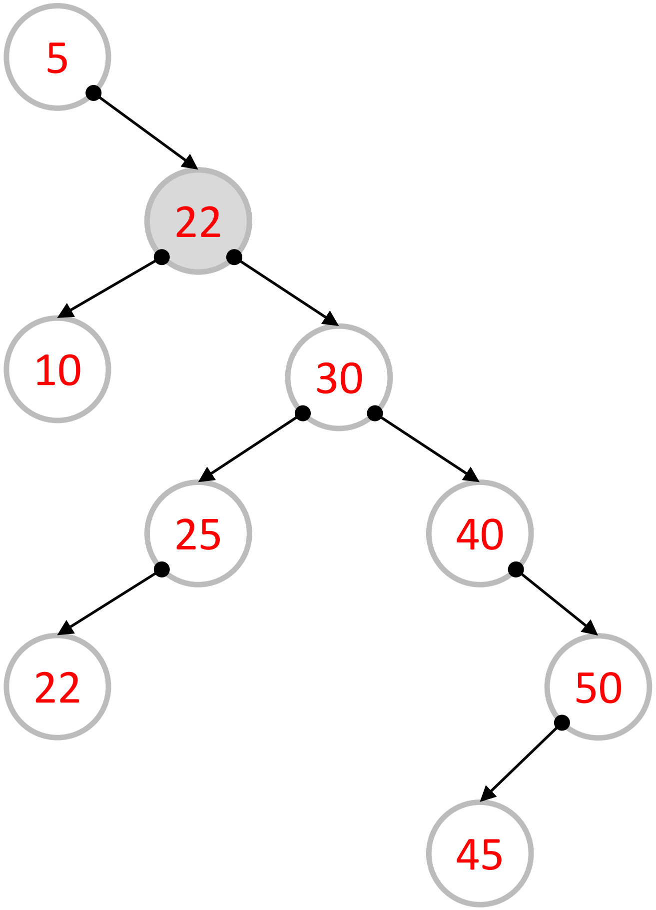
- clock rate of a single CPU core currently limited to ≈ 4GHz
- single CPU core processing power NO longer doubling every 18 months
- Intel, AMD, Sun, IBM, … producing multicore CPUs instead
- typical desktop has 4 cores with each core capable of executing 2 threads [hyper-threading] giving a total of 8 concurrent threads
- top-of-range desktop 2014 16 threads, 2016 32 threads, … [Moore's Law and Joy's Law]
- need to be able to exploit *cheap* threads on multicore CPUs
- locked based solutions are simply not scalable as locks INHIBIT parallelism
- need to explore lockless data structures and algorithms

Consider a Binary Search Tree (BST) as an example

- contains(*key*)
  returns 1 if key in tree
- add(*key*)
  always adds to a leaf node
- remove(*key*)
  3 cases depending if node has zero, one or two children
- operations on tree normally protected by a per tree lock which inhibits parallelism
- why can't operations be performed in parallel?
- how much parallelism is possible?



BST Operations



- add (50) [single pointer updated]
- add(45) [single pointer updated]
- remove(45) – NO children [one pointer updated]
- remove(25) – ONE child [single pointer updated]
- remove(20) – TWO children

  find node (20)
  find smallest key in its right sub tree (22)
  overwrite key 20 with 22
  remove old node 22 (will have zero or one child)
  [key and a pointer updated]

- variations

  find largest key in left sub-tree instead of smallest key in right sub tree
  move node instead of value

Concurrent add operations

- concurrently add(*27*) <u>and</u> add(*50*)

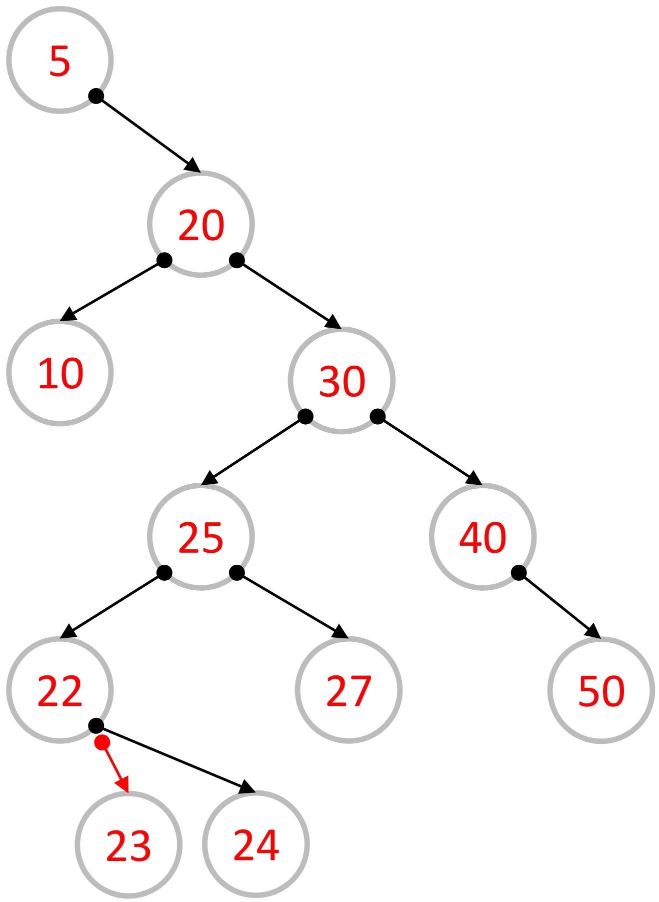
  OK if adding to different nodes

- concurrently add(*23*) <u>and</u> add(*24*)

  problem as adding to same leaf node

  result depends on how steps of operations are interleaved [pointer updates]

  could work correctly, BUT...
  if there is a conflict ONLY one node may be added [23 or 24, BUT still a valid tree]



Concurrent remove operations

- concurrently remove(*21*) <u>and</u> remove(*27*)

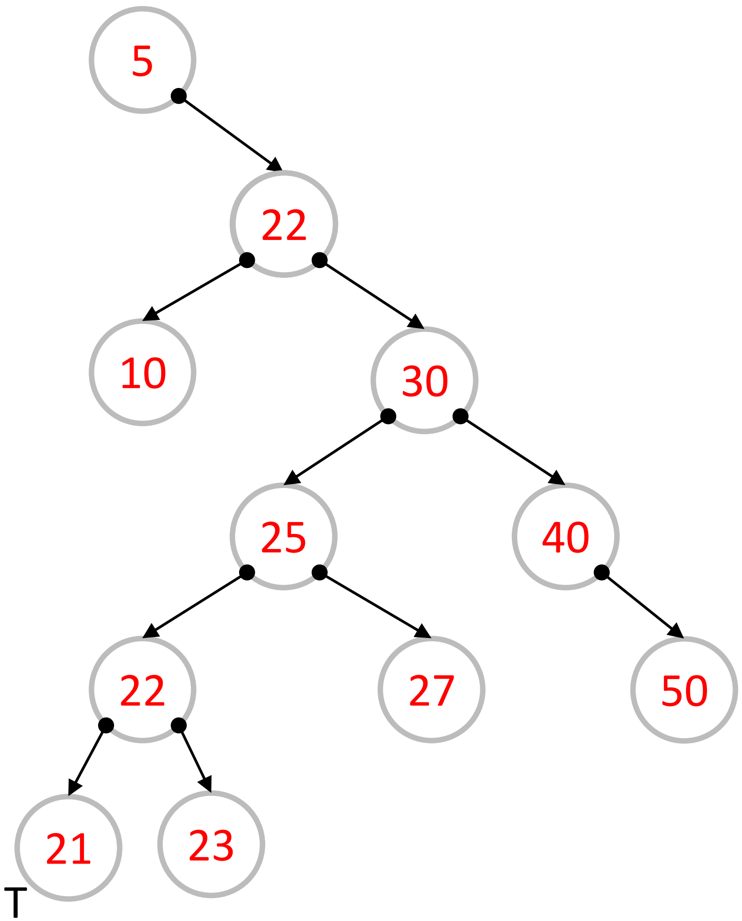
  OK as both are leaf nodes [have NO children]

- concurrently remove(*20*) <u>and</u> remove(*22*)

  smallest key in 20's right sub tree is 22
  result depends on how steps of operations are interleaved [key and pointer updates]
  could work correctly, BUT ...
  one possible interleave is as follows

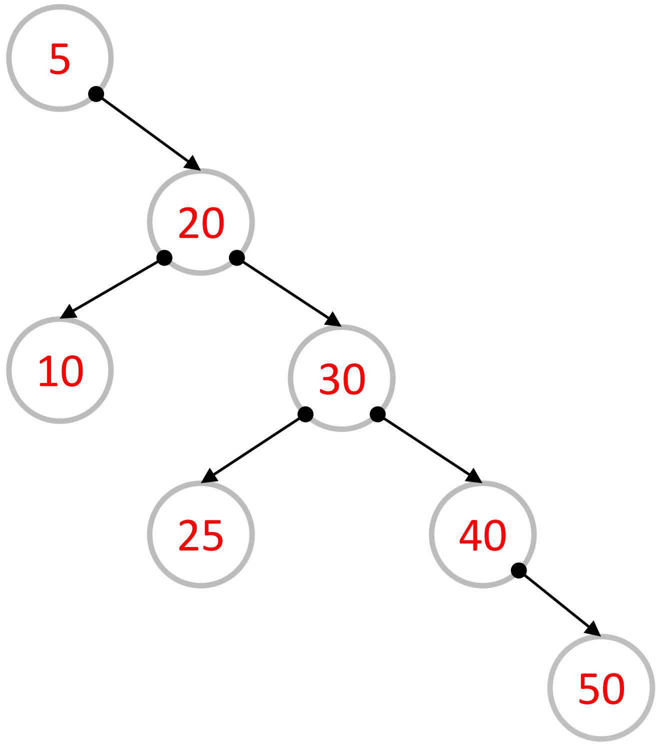
  both operations find 22
  20 is overwritten with 22
  old node 22 removed [by both operations], BUT
  22 still in tree!

  other interleaves possible



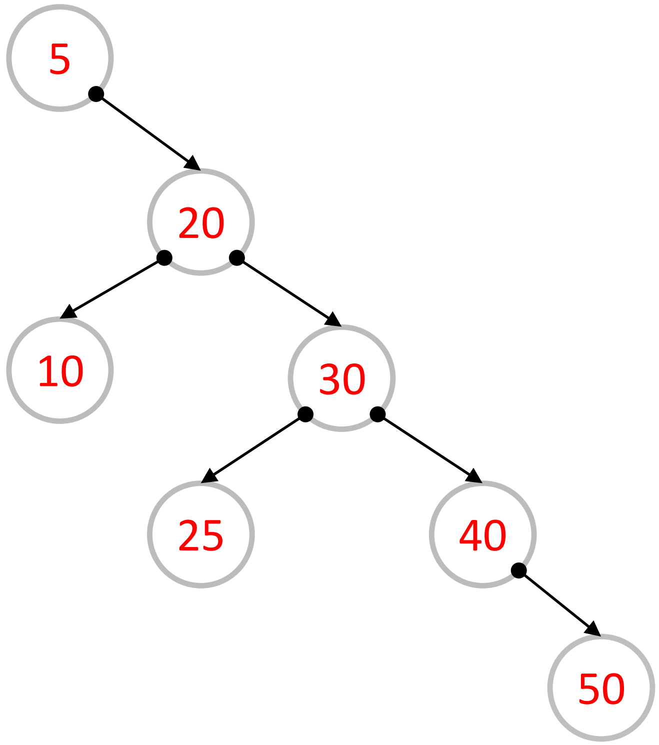
Concurrent add and remove operations

- concurrently add(*50*) and remove(*25*)
- OK as modifying links in different nodes



Concurrent add and remove operations...

- concurrently add(*50*) <u>and</u> remove(*40*)
- result depends on how steps of operations are interleaved [key and pointer updates]
- could work correctly, BUT ...
- one possible interleave as follows
- 40 deleted, BUT ...
- 50 also deleted as attached to 40



Concurrent Operations on a BST

- concurrent operations ARE possible
- probability of a conflict inversely proportional to size of tree
- conflicts proportional to number of concurrent operations
- with a large tree, conflicts between operations will be rare
- with a large tree, should be able to achieve a linear speedup proportional to number of threads provided that conflicts can be detected and resolved
- protecting tree with a single lock is pessimistic as it assumes conflicts will occur resulting in NO parallelism
- a lockless algorithm is optimistic as it assumes conflicts unlikely to occur and, when they are detected, they are resolved – allows parallelism while there are no conflicts which hopefully is most of the time