Parallelising the computational algebra system GAP

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The GAP system

- System for Computational Discrete Algebra
- Interpreted language
- Problem: Parallelising the GAP language (for shared memory systems) as part of the HPC-GAP project
  - Thousands of established users
  - Hundreds of thousands of lines of GAP code in the standard distribution
  ⇒ Limits on language redesign
GAP Users

- How many of their resources (time, effort, money) can they invest in parallelism?
- Spectrum ranges from “little” to “a lot”.
- Pure domain experts (mathematicians)
- Domain experts who need performance
- Parallelism experts
Correctness and performance

- Difficult to reconcile in parallel programming (non-determinism, race conditions, deadlocks)
- But: Both are important
- Make correctness easy even when programming for performance
  - Safe default behavior
  - Flag concurrency errors aggressively
Data spaces

- Each GAP object belongs to exactly one data space
- Thread-local data spaces: One per thread.
  - All objects originate in a thread-local data space
  - May migrate to other data spaces later
  - Present the illusion of a mostly sequential environment
  - Ease of use for parallelism non-experts
  - Limited concurrency potential
Data spaces (continued)

- Shared data spaces
  - Have an associated R/W lock
  - Need to be locked and unlocked explicitly before access

- One public data space
  - Contains only atomic objects
  - Can be accessed without explicit locking
Object migration

- Threads interact by migrating objects
- Migrating an object changes its data space membership
- Does not copy its contents
- Cheap operation (update a C pointer)
- Variants:
  - Thread-local -> Thread-local: Message passing
  - Thread-local -> Shared, Public: Sharing
  - Shared -> TL: Privatization
Parallelism for non-experts

- Domain experts see a sequential world.
  - Their program is one thread
  - Indistinguishable from sequential code
  - Accesses only thread-local data directly
  - May use parallelised libraries with a sequential API

- If you want more, we provide skeletons:
  - result := ParList(list, x -> f(x), NumWorkers);
  - ParList() splits ‘list’ in segments, migrating them to workers
  - Worker threads perform x ->f(x) thread-locally
  - Results migrated back to main thread
A closer look at migration

- Thread 1: `SendChannel(ch, a);`
- Thread 2: `b := ReceiveChannel(ch);`
- Object is migrated:
  - From thread 1’s thread-local data space
  - Via the channel’s shared data space
  - To thread 2’s thread-local data space
- Note: Variables `a` and `b` both reference the same object at the end
  - Not classic message passing
  - Race conditions possible?
Data race protection

- Primitives protect any access to an object
  - WriteGuard(): Requires exclusive access
  - ReadGuard(): Requires shared access
  - Both check the object’s data space descriptor

- All object accesses are:
  - Either: protected by the appropriate primitive
  - Or: statically verified to be safe.

⇒ Data races cannot occur
Example

- This code produces an error:
  
  ```
  local c, z;
  c := 2;
  z := ParList([1..100], x->x+c, NumWorkers);
  ```

- Why?
  - `c` is in the main thread’s thread-local data space
  - Worker threads try to access it

- Solution:
  
  ```
  z := ParList([1..100], Publish(x->x+c), NumWorkers);
  ```
Deadlock protection

- There must be a partial order ‘>’ on shared data spaces
- Users do not need to specify this partial order
- If a thread holds a lock on DS1 while it acquires a lock on DS2, DS1 > DS2 must hold
- If not, an error is raised
- GAP kernel tracks sequences of lock operations
- Ensures that there are no cycles in that relation
Summary

- Thread-local data spaces: sequential core
- Shared & public data spaces, migration: provide concurrency
- Protection from data races and deadlocks
- Skeletons to encode parallel algorithms
Non-interference

- Owicki-Gries (Acta Informatica 1976)
- Principle: Actions in one process don’t invalidate assertions in another
- A, B programs
- B doesn’t interfere with A:
  \[
  \{ \text{Pre}_A \} \ A \ { \text{Post}_A } \ \\
  \Rightarrow \ { \text{Pre}_A } \ A \ || \ B \ { \text{Post}_A } 
  \]
Ensuring non-interference

- Programmers may not formally prove correctness, but still consider assertions informally
  - “What properties hold at what point in the program”
- Minimize proof obligations for non-interference
- Make non-interference the default
- Make interference explicit
- Alert programmer to potential interference
- Composability of correctness proofs
Software Transactional Memory

- Performance concerns
  - High constant overhead
  - Works well for some problems, not for others
- Open nesting needed?
  - Unintuitive, requires expertise
- We can still use STM for fine-grained locking