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Grace: Safe Multithreaded Programming for C/C++

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Concurrency Problems

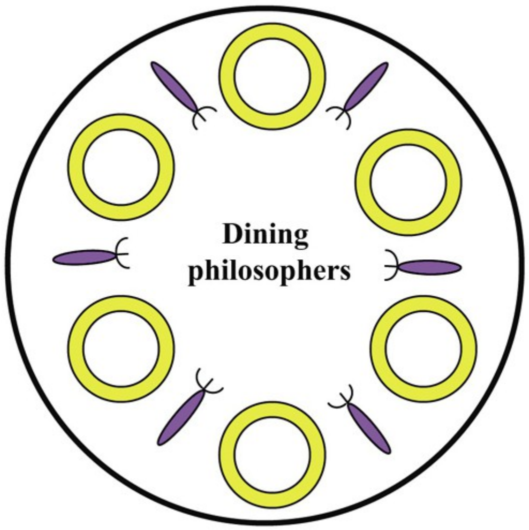
- Cyclic lock acquisition

  → deadlocks
- Unguarded update

  → race conditions
- Unguarded, interleaved updates

  → atomicity violations
- Threads scheduled in unexpected order

  → order violations



Solution: Grace

- Locks converted to no-ops

  → ~~deadlocks~~
- All updates committed deterministically (sequential)

  → ~~race conditions~~
- Threads run atomically

  → ~~atomicity violations~~
- Threads execute in program order (sequential)

  → ~~order violations~~

Sequential Semantics (1)

- Restricted to fork-join parallelism

```
// Run f(x) and g(y) in parallel
t1 = spawn f(x);
t2 = spawn g(y);

// Wait for both to complete
sync;
```

Sequential Semantics (2)

- Program is *behaviorally* turned into its sequential counterpart → serial elision

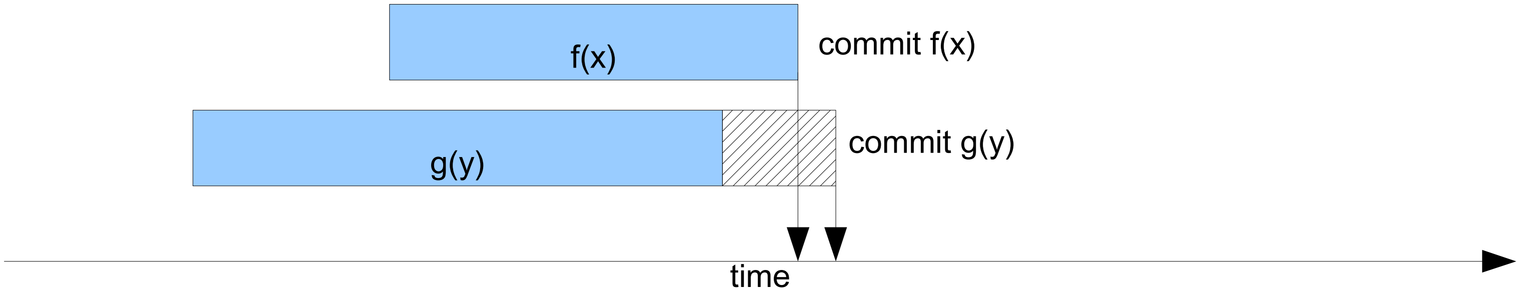
```
// Run f(x) and g(y) in parallel.
t1 = ~~spawn~~ f(x);
t2 = ~~spawn~~ g(y);
// Wait for both to complete
~~sync~~;
```

  - thread spawn → sequential
  - lock operations → no-ops

Sequential Semantics (3)

- Threads run concurrently
- Commited in sequential order
  - Each thread waits for its logical predecessor

```
// Run f(x) and g(y) in parallel.
t1 = ~~spawn~~ f(x);
t2 = ~~spawn~~ g(y);
// Wait for both to complete
~~sync~~;
```



Transactional Memory required

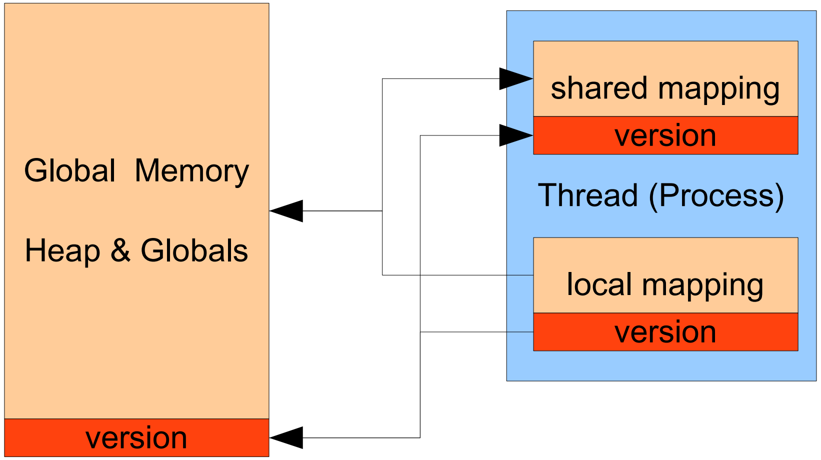
Transactional Memory (1)

- Updates are committed in program order
  - Some form of transactional memory required
  - `atomic` clause for short transactions
  - What about long-lived transactions?

- Solution: use processes instead of threads (`forks`)
  - Standard memory protection functions
  - Signal handlers to track reads/writes
  - Shared address space

Transactional Memory (2)

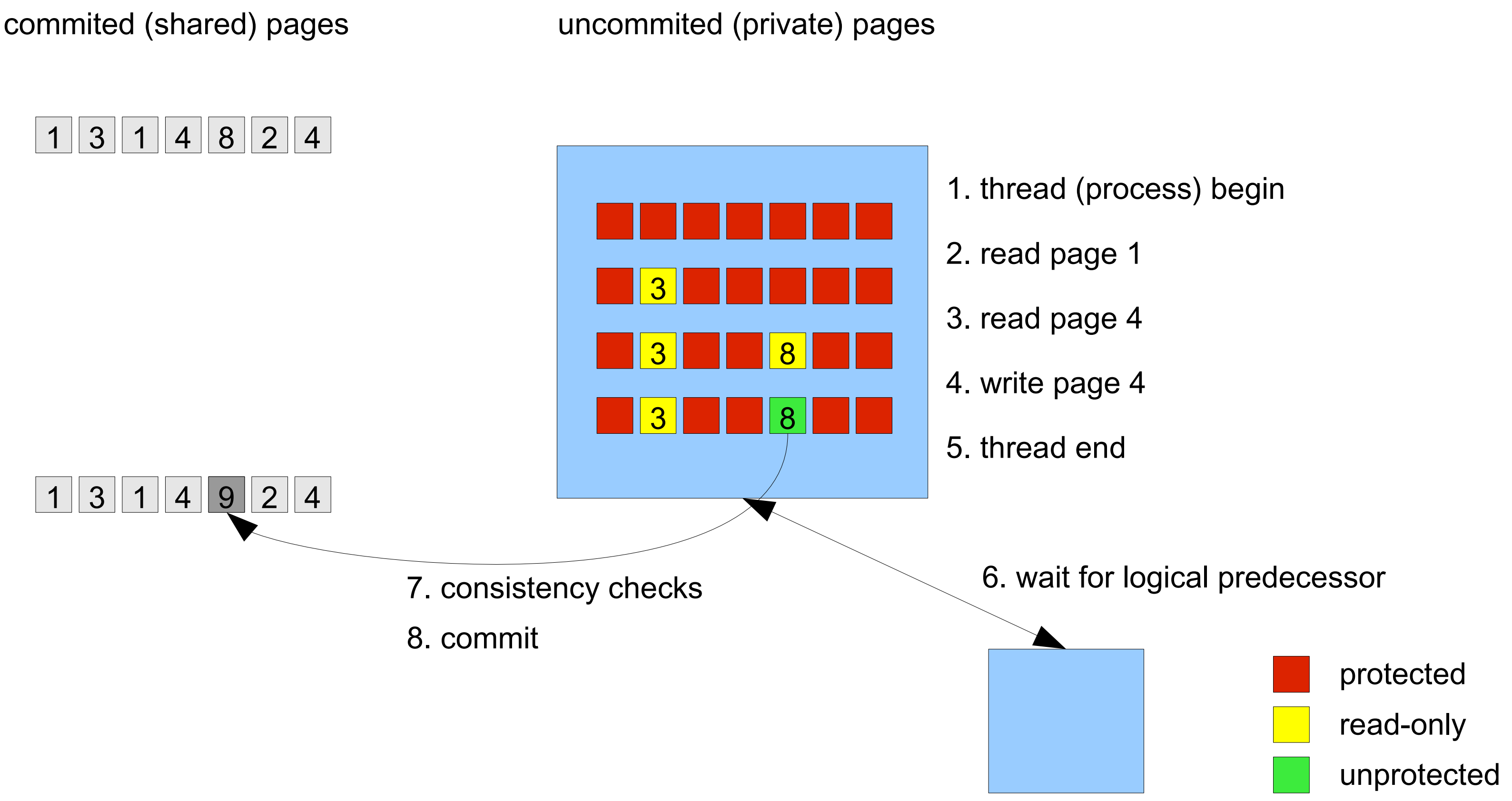
- Memory mapped files → shared memory
  - Array of version numbers (one per page)
  - Shared mapping → latest commit state
  - Local (per-process), copy-on-write mapping → working set



Transactional Memory (3)

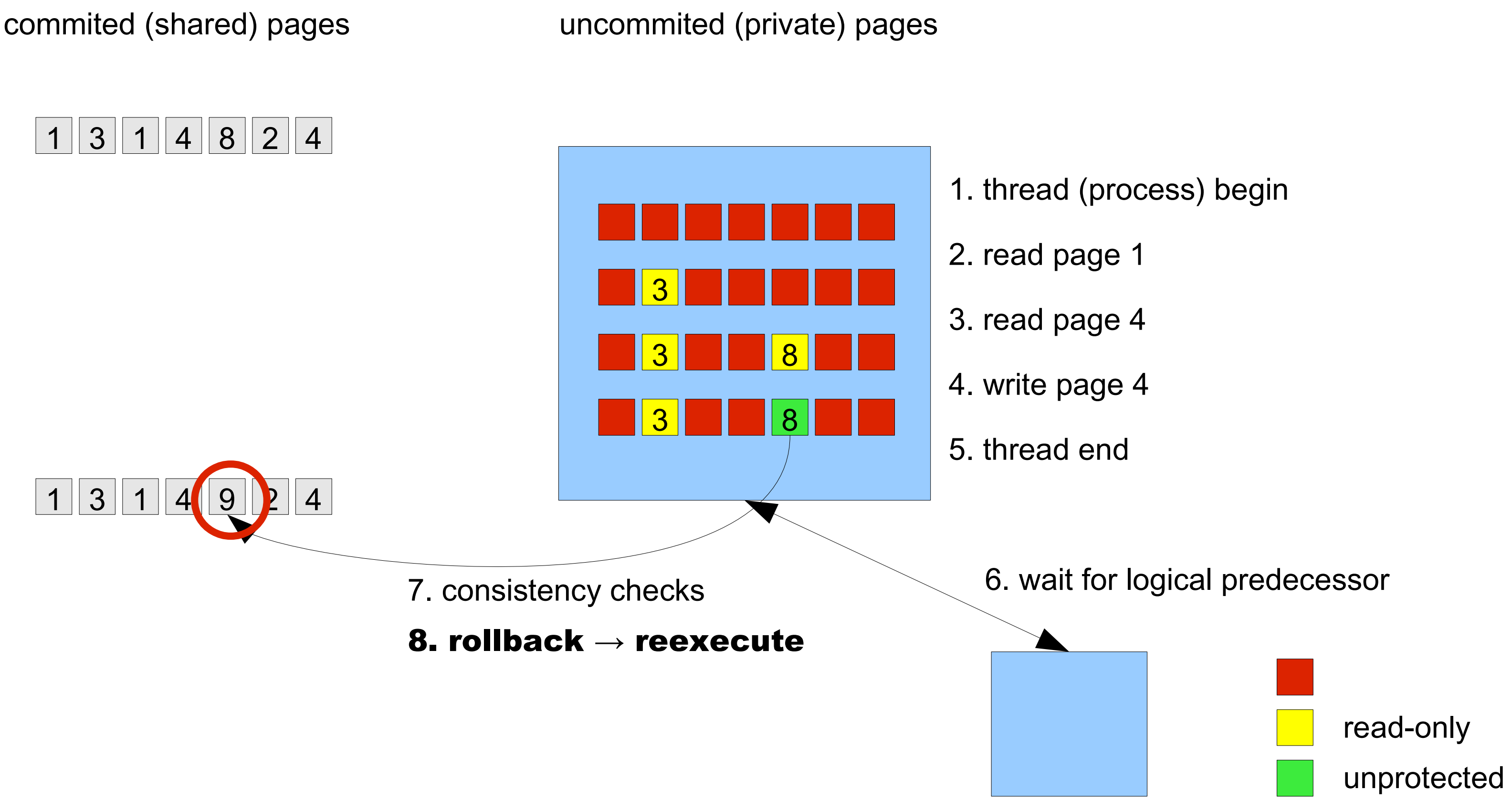
- Local mapping
  - Protection of all pages set to `PROT_NONE`
  - First access triggers a pagefault (`SEGV`)
    - Read: set protection to `PROT_READ`
    - Write: set protection to `PROT_READ | PROT_WRITE` and update version
  - Copy on write semantics!

Transactional Memory (4) - commit



1. thread (process) begin
2. read page 1
3. read page 4
4. write page 4
5. thread end
6. wait for logical predecessor
7. consistency checks
8. commit

Transactional Memory (5) - rollback



1. thread (process) begin
2. read page 1
3. read page 4
4. write page 4
5. thread end
6. wait for logical predecessor
7. consistency checks

8. rollback → reexecute

Thread Execution (1)

- Initialization
  - Save execution context
    - program counter
    - registers
    - stack contents
  - Set page protection to `PROT_NONE`
- Execution
  - Track page accesses over `SEGV` protection faults
  - Version control

Thread Execution (2)

- Completion
  - Commit attempts at
    - end of main()
    - end of individual thread
    - right before a child thread spawn
    - right before joining another thread
  - No commit required when no change

Thread Execution (3)

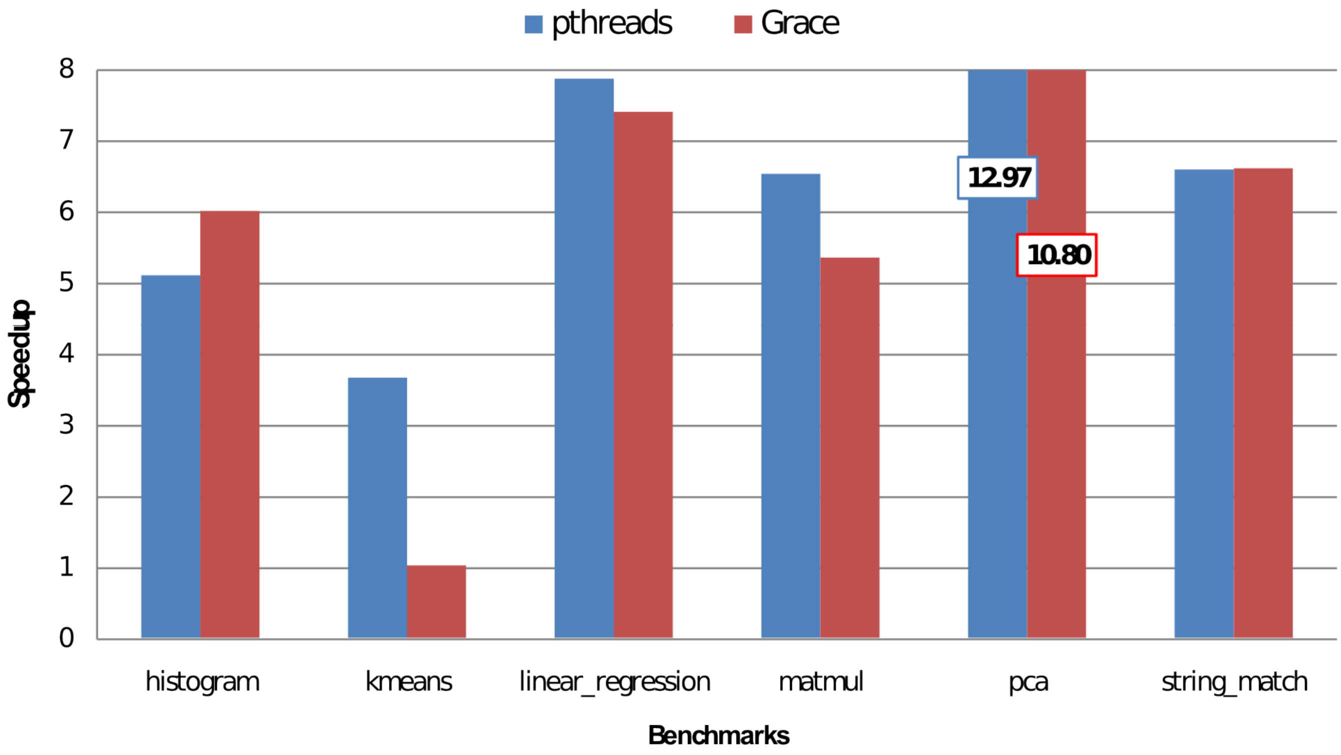
- Committing
  - lock all memory mappings (interprocess mutex)
  - perform consistency checks (check version numbers)
    - success: copy contents of each page into shared images
    - fail: rollback and reexecute

Benchmarks

histogram	Analyzes images' RGB components
kmeans	Iterative clustering of 3-D points
linear_regression	Computes best fit line for a set of points
matmul	Recursive matrix-multiply
pca	Principal component analysis on matrix
string_match	Searches file for encrypted word

Benchmarks

	Commits	Rollbacks	Pages Read	Pages Written
histogram	9	0	7	6
kmeans	6273	4887	404	2
linear_reg	9	0	6	5
matmul	11	0	4100	1865
pca	22	0	3	2
string_match	11	0	6	4



Verification – Deadlocks

```
thread1() {
    lock(A);
    lock(B);
    // ...do something
    unlock(B);
    unlock(A);
}

thread2() {
    lock(B);
    lock(A);
    // ...do something
    unlock(A);
    unlock(B);
}
```

Verification – Atomicity violations

```
thread1() {
    if (thd->proc_info) {
        fputs(thd->proc_info, ...);
    }
}

thread2() {
    thd->proc_info = NULL;
}
```

Verification – Race conditions

```
int counter = 0;

increment() {
    print(counter);
    int temp = counter;
    temp++;
    counter = temp;
    print(counter);
}

thread1() { increment(); }
thread2() { increment(); }
```

Verification – Order violations

```
char* proc_info;

thread1() {
    proc_info = malloc(256);
}

thread2() {
    // maybe executed before thread1()
    strcpy(proc_info, “abc“);
}

main() {
    spawn thread1();
    spawn thread2();
}
```

Questions?