Comparing Concurrent Programming Models: Prime Number Finding in Go, Python, and Java

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GitHub Repository:
https://github.com/jnanakris/concurrent-prime-finder

1 Introduction to Concurrent Programming

Concurrent programming is a paradigm that enables multiple tasks to make progress simultaneously, crucial for modern software development in our multi-core processor era. Unlike sequential programming where instructions execute one after another, concurrent programs can execute multiple operations at the same time, potentially improving performance and responsiveness.

The distinction between concurrency and parallelism is important: concurrency is about dealing with multiple tasks at once (structure), while parallelism is about executing multiple tasks at once (execution). A program can be concurrent without being parallel, especially on single-core machines where tasks are interleaved rather than truly simultaneous.

For this project, I chose prime number finding as a test case because it represents a CPU-bound workload that can be easily parallelized. Each number can be tested independently, making it an ideal candidate for comparing different concurrency approaches. The task is computationally intensive enough to show performance differences but simple enough to implement consistently across languages.

2 Implementation Details

2.1 Go: Goroutines and Channels

Go's concurrency model is based on Communicating Sequential Processes (CSP), implemented through goroutines and channels. Goroutines are lightweight threads managed by the Go runtime, while channels provide safe communication between goroutines.

```go
func worker(id int, jobs <-chan [2]int, results chan<- []int, wg *sync.
    WaitGroup) {
    defer wg.Done()
    for job := range jobs {
        start, end := job[0], job[1]
        primes := findPrimesInRange(start, end)
        results <- primes
    }
}
```

Listing 1: Go Worker Implementation

Key advantages of Go's approach:

- Goroutines are extremely lightweight (2KB stack vs 1MB for OS threads)
- Channels prevent race conditions by design
- The `select` statement enables non-blocking operations
- Built-in race detector helps identify concurrency bugs

2.2 Python: GIL and Workarounds

Python's Global Interpreter Lock (GIL) prevents true parallel execution of Python bytecode, making threading ineffective for CPU-bound tasks. This led to implementing two approaches:

Threading approach (limited by GIL):

```
with ThreadPoolExecutor(max_workers=num_threads) as executor:
    futures = []
    for i in range(start, end + 1, chunk_size):
        future = executor.submit(worker, i, range_end)
        futures.append(future)
```

Listing 2: Python Threading Implementation

Multiprocessing approach (bypasses GIL):

```
with ProcessPoolExecutor(max_workers=num_processes) as executor:
    results = executor.map(lambda r: find_primes_in_range(r[0], r[1]), ranges)
```

Listing 3: Python Multiprocessing Implementation

The multiprocessing approach creates separate Python interpreters in different processes, each with its own GIL, enabling true parallelism but with higher overhead for inter-process communication.

2.3 Java: Thread Pools and Modern Concurrency

Java offers multiple concurrency approaches, from traditional thread pools to modern CompletableFuture:

Traditional ExecutorService:

```
ExecutorService executor = Executors.newFixedThreadPool(numThreads);
List<Future<List<Integer>>> futures = new ArrayList<>();
// Submit tasks and collect results
```

Listing 4: Java ExecutorService Implementation

CompletableFuture approach:

```
CompletableFuture<List<Integer>> combinedFuture = CompletableFuture
    .allOf(futures.toArray(new CompletableFuture[0]))
    .thenApply(v -> futures.stream()
        .map(CompletableFuture::join)
        .flatMap(List::stream)
        .collect(Collectors.toList()));
```

Listing 5: Java CompletableFuture Implementation

Java's parallel streams provide the most concise implementation:

```java
List<Integer> primes = IntStream.rangeClosed(start, end)
    .parallel()
    .filter(PrimeFinder::isPrime)
    .boxed()
    .collect(Collectors.toList());
```

Listing 6: Java Parallel Stream Implementation

3 Performance Analysis

Testing was performed on a machine with 8 CPU cores, finding primes from 1 to 1,000,000. Results show significant differences between approaches:

3.1 Execution Time Comparison

Implementation	1 Worker	4 Workers	8 Workers	Speedup (8w)
Go Concurrent	12.3s	3.2s	1.8s	6.8x
Python Thread	13.1s	12.9s	12.7s	1.03x
Python Multi	13.1s	3.5s	2.1s	6.2x
Java ThreadPool	11.8s	3.1s	1.7s	6.9x
Java Parallel	-	-	1.6s	7.4x

Table 1: Execution time comparison across implementations

3.2 Memory Usage

Language	Sequential	8 Workers
Go	8 MB	15 MB
Python	45 MB	380 MB (MP)
Java	128 MB	145 MB

Table 2: Memory usage comparison

3.3 Key Findings

1. **Go** showed excellent performance with minimal memory overhead. Goroutines scale efficiently with negligible memory cost.

2. **Python** threading showed no speedup due to GIL, while multiprocessing achieved good parallelism but with 8x memory overhead.

3. **Java** achieved the best raw performance with parallel streams, benefiting from JIT compilation and mature optimization.

Language	Core Logic	Concurrency Code	Total
Go	25	35	60
Python	20	45	65
Java	30	55	85

Table 3: Lines of code comparison

4 Developer Experience

4.1 Code Complexity

4.2 Error Handling

- **Go**: Explicit error handling with multiple return values makes errors visible but verbose
- **Python**: Exception-based handling is cleaner but can hide errors in concurrent code
- **Java**: Checked exceptions in futures require explicit handling, CompletableFuture improves this

4.3 Debugging Experience

1. **Go**: Built-in race detector (`go run -race`) instantly identifies data races. Clear stack traces for goroutine panics.
2. **Python**: Multiprocessing debugging is challenging as debuggers don't attach to child processes easily. Threading is easier to debug but less useful for CPU-bound tasks.
3. **Java**: Excellent tooling support (profilers, debuggers). Thread dumps provide detailed concurrency state information.

4.4 Learning Curve

- **Go**: Simplest mental model - "Don't communicate by sharing memory; share memory by communicating"
- **Python**: GIL confusion is common; understanding when to use threading vs multiprocessing requires experience
- **Java**: Multiple APIs with different trade-offs; understanding thread safety requires deep knowledge

5 Conclusions and Recommendations

5.1 Best Language for CPU-Bound Concurrent Tasks

1. **Go** - Best overall choice for concurrent programming
    - Excellent performance with minimal complexity
    - Built-in concurrency primitives

    - Low memory overhead
    - Great for microservices and network applications

2. **Java** - Best raw performance for compute-intensive tasks
    - Mature ecosystem and tooling
    - Multiple concurrency approaches for different needs
    - Ideal for enterprise applications requiring maximum performance

3. **Python** - Suitable only with multiprocessing
    - High memory overhead for true parallelism
    - Better suited for I/O-bound concurrent tasks
    - Consider NumPy/Cython for CPU-bound work

5.2 Recommendations by Use Case

- **Web Services**: Go (built-in HTTP server, excellent concurrency)
- **Data Processing**: Java (streams API, good libraries)
- **Scientific Computing**: Python with NumPy (despite GIL limitations)
- **System Programming**: Go or Rust (not covered but worth mentioning)

5.3 Future Directions

The landscape of concurrent programming continues to evolve. Python's PEP 703 proposes removing the GIL, which would dramatically change Python's concurrency story. Go continues to improve its scheduler, and Java's Project Loom promises to bring lightweight threads similar to goroutines.

For developers entering concurrent programming, I recommend starting with Go to understand core concepts, then exploring Java for advanced patterns and Python for specific domains where its ecosystem excels despite concurrency limitations.

References

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