

# Optimizing Genetic Algorithms Using the Binomial Distribution

Vincent A. Cicirello <sup>a</sup>

Computer Science, School of Business, Stockton University, 101 Vera King Farris Dr, Galloway, NJ, USA  
vincent.cicirello@stockton.edu

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**Abstract:** Evolutionary algorithms rely very heavily on randomized behavior. Execution speed, therefore, depends strongly on how we implement randomness, such as our choice of pseudorandom number generator, or the algorithms used to map pseudorandom values to specific intervals or distributions. In this paper, we observe that the standard bit-flip mutation of a genetic algorithm (GA), uniform crossover, and the GA control loop that determines which pairs of parents to cross are all in essence binomial experiments. We then show how to optimize each of these by utilizing a binomial distribution and sampling algorithms to dramatically speed the runtime of a GA relative to the common implementation. We implement our approach in the open-source Java library Chips-n-Salsa. Our experiments validate that the approach is orders of magnitude faster than the common GA implementation, yet produces solutions that are statistically equivalent in solution quality.

## 1 INTRODUCTION


The simulated evolutionary processes of genetic algorithms (GA), and other evolutionary algorithms (EA), are stochastic and rely heavily on randomized behavior. Mutation in a GA involves randomly flipping bits. Cross points in single-point, two-point, and  $k$ -point crossover are chosen randomly. Uniform crossover uses a process similar to mutation to randomly choose which bits to exchange between parents. The decision of whether to cross a pair of parents during a generation is random. Selection operators usually randomize the selection of the population members that survive.

Random behavior pervades the EA. Thus, how randomness is implemented significantly impacts performance. Many have explored the effects of the pseudorandom number generator (PRNG) on solution quality (Krömer et al., 2018; Rajashekharan and Velayutham, 2016; Krömer et al., 2013; Tirronen et al., 2011; Reese, 2009; Wiese et al., 2005a; Wiese et al., 2005b; Cantú-Paz, 2002), and others the effects of PRNG on execution times (Cicirello, 2018; Nesmachnow et al., 2015). Choice of PRNG isn't the only way to optimize an EA's random behavior. Our open source Java library Chips-n-Salsa (Cicirello, 2020) optimizes randomness of its EAs and metaheuristics beyond the PRNG, such as in the choice of algorithms for Gaussian random numbers and random integers in an interval. Section 2 further discusses related work.

This paper focuses on optimizing the randomness of bit-flip mutation, uniform crossover, and the determination of which pairs of parents to cross. Formally, all three of these are binomial experiments, with the relevant GA control parameters serving as the success probabilities for a sequence of Bernoulli trials. This leads to our approach (Section 3) to each that replaces explicit iteration over bits or the population with a binomial distributed random variable and an efficient sampling algorithm.

Others, such as Ye et al, previously observed that the number of bits mutated by the standard bit-flip mutation follows a binomial distribution (Ye et al., 2019). However, examining the source code of their implementation (Ye, 2023) reveals that they generate binomial random variates by explicitly iterating  $n$  times for a bit-vector of length  $n$ , generating a total of  $n$  uniform variates in the process. Their approach refactored where the explicit iteration occurs, but did not eliminate it. Ye et al were not trying to optimize the runtime of the traditional GA. Rather, their reason for abstracting the mutated bit count was to enable exploring alternative mutation operators, such as their normalized bit mutation (Ye et al., 2019) in which the number of mutated bits follows a normal distribution rather than a binomial.

In our approach, presented in detail in Section 3, we eliminate the  $O(n)$  uniform random values generated during explicit iteration over bits. Instead, we use an efficient algorithm for generating binomial

<sup>a</sup>  <https://orcid.org/0000-0003-1072-8559>

random variates (Kachitvichyanukul and Schmeiser, 1988) that requires only  $O(1)$  random numbers on average. Additionally, we use a more efficient sampling algorithm for choosing which bits to mutate. Ours is the first approach to use the binomial distribution in this way to optimize the runtime of bit-flip mutation. Furthermore, we also apply the technique to optimize uniform crossover as well as the process of selecting which pairs of parents to cross.

Our experiments (Section 4) demonstrate the massive gains in execution speed that result from this approach. We will see that the optimized bit-flip mutation uses 70%-99% less time than the common implementation. The optimized uniform crossover uses 61%-99% less time than the common implementation. A GA using the optimized decision of which parents to cross, as well as the optimized operators, uses 78%-97% less time than the common implementation. We implemented the approach in the open source library Chips-n-Salsa (Cicirello, 2020) and released the code of the experiments as open source to enable easily replicating the results. We wrap up with a discussion in Section 5.

## 2 RELATED WORK

Several have shown that higher quality PRNGs that pass more rigorous randomness tests do not lead to better fitness, and that solution quality is insensitive to PRNG (Rajashekharan and Velayutham, 2016; Tirronen et al., 2011; Wiese et al., 2005a; Wiese et al., 2005b; Cantú-Paz, 2002). For example, the ablation study of Cantú-Paz shows that the PRNG used for selection, crossover, and mutation does not affect fitness, and that even using true random numbers does not improve fitness (Cantú-Paz, 2002). Thus, choice of PRNG has little, if any, impact on solution fitness.

Fewer have studied the impact of the PRNG on execution times, but the research that exists shows potential for massive efficiency gains. Nesmachnow et al analyzed the effects of several implementation factors on the runtime of EAs implemented in C (Nesmachnow et al., 2015). They showed 50%-60% improvement in execution times by using state-of-the-art PRNGs such as R250 (Kirkpatrick and Stoll, 1981) or Mersenne Twister (Matsumoto and Nishimura, 1998) rather than the C library’s `rand()` function. Cicirello showed that an adaptive permutation EA is 25% faster (Cicirello, 2018) when using the PRNG Split-Mix (Steele et al., 2014) rather than the classic linear congruential (Knuth, 1998), and by implementing Gaussian mutation (Hinterding, 1995) with the zigurat algorithm (Marsaglia and Tsang, 2000; Leong

Table 1: Notation shared across algorithm pseudocode.

$B(n, p)$	binomial distributed random integer
$\text{FlipBit}(v, i)$	flips bit $i$ of vector $v$
$\text{Length}(v)$	simple accessor for length of $v$
$\text{Rand}(a, b)$	random real in $[a, b)$
$\text{Rand}(a)$	random integer in $[0, a)$
$\text{Sample}(n, k)$	sample $k$ distinct integers from $\{0, 1, \dots, n-1\}$
$\oplus, \wedge, \vee, \neg$	bitwise XOR, AND, OR, and NOT

et al., 2005) rather than the polar method (Knuth, 1998). There are also studies on the impact of PRNG and related algorithmic components on the runtime performance of randomized systems other than EAs, such as Metropolis algorithms (Macias-Medri et al., 2023). Others explored the effects of programming language choice on GA runtime (Merelo-Guervós et al., 2017; Merelo-Guervós et al., 2016).

The EAs of Chips-n-Salsa (Cicirello, 2020) optimize randomness in ways beyond the choice of PRNG. For example, Chips-n-Salsa uses the algorithm of Lemire for random integers in an interval (Lemire, 2019) as implemented in the open source library  $\rho\mu$  (Cicirello, 2022b), which is more than twice as fast as Java’s built-in method due to a significantly faster approach to rejection sampling. Such bounded random integers are used by EAs in a variety of ways, such as the random cross sites for single-point, two-point, and  $k$ -point crossover.

## 3 APPROACH

We now present the details of our approach. In Section 3.1, we formalize the relationship between different processes within a GA and binomial experiments. In Section 3.2, we describe our approach to random sampling. We derive our optimizations of random bit-mask generation, mutation, and uniform crossover in Sections 3.3, 3.4, and 3.5, respectively. We show how to optimize the process of determining which pairs of parents to cross, as well as putting all of the optimizations together in Section 3.6.

Table 1 summarizes the notation and functions shared by the pseudocode of the algorithms throughout this section. We assume that indexes into bit-vectors begin at 0. The runtime of  $\text{FlipBit}(v, i)$ ,  $\text{Length}(v)$ , and  $\text{Rand}(a, b)$  is  $O(1)$ . The runtime of the bitwise operators is  $O(n)$  for vectors of length  $n$ . Our bit-vector implementation utilizes an array of 32-bit integers, enabling exploiting implicit parallelism, such as for bitwise operations (e.g., a bitwise operation on two bit-vectors of length  $n$  requires  $\frac{n}{32}$  bitwise operations on 32-bit integers).

```

1 function Sample( $n, k$ )
2   if  $k \geq \frac{n}{2}$  then
3     return ReservoirSample( $n, k$ )
4   end
5   if  $k \geq \sqrt{n}$  then
6     return PoolSample( $n, k$ )
7   end
8   return InsertionSample( $n, k$ )
9 end

```

Algorithm 1: Random sampling.

### 3.1 Binomial Variates and the GA

A Bernoulli trial is an experiment with two possible outcomes, usually success and failure, and specified by success probability  $p$ . A binomial experiment is a sequence of  $n$  independent Bernoulli trials with identical  $p$  (Larson, 1982). The binomial distribution  $B(n, p)$  is the discrete probability distribution of the number of successes in an  $n$ -trial binomial experiment with parameter  $p$ .

Our approach observes that GA mutation of a bit vector of length  $n$  is a binomial experiment with  $n$  trials, but the possible outcomes of each trial are “flip-bit” and “keep-bit” instead of success and failure. The number of bits flipped while mutating a bit vector of length  $n$  must therefore follow binomial distribution  $B(n, p_m)$ , where  $p_m$  is the mutation rate. Uniform crossover of a pair of bit vectors of length  $n$  is also a binomial experiment with  $n$  trials, with the number of bits exchanged between parents following binomial distribution  $B(n, p_u)$ , where  $p_u$  is the probability of exchanging a bit between the parents. Choosing which pairs of parents to cross is likewise a binomial experiment with  $n/2$  trials for population size  $n$ , and the number of crosses during a generation follows binomial distribution  $B(n/2, p_c)$  for crossover rate  $p_c$ .

We generate binomial random variates  $B(n, p)$  with the BTPE algorithm (Kachitvichyanukul and Schmeiser, 1988), whose runtime is  $O(1)$  (Cicirello, 2024b). This algorithm choice is critical to later analysis, as many alternatives do not have a constant runtime (Kuhl, 2017; Knuth, 1998).

### 3.2 Sampling

To sample  $k$  distinct integers from the set  $\{0, 1, \dots, n-1\}$ , we implement `Sample( $n, k$ )` using a combination of reservoir sampling (Vitter, 1985), pool sampling (Goodman and Hedetniemi, 1977), and insertion sampling (Cicirello, 2022a), choosing the most efficient based on  $k$  relative to  $n$ .

Algorithms 1 and 2 provide pseudocode of the details. See the original publications of the three sam-

```

1 function ReservoirSample( $n, k$ )
2    $s \leftarrow$  an array of length  $k$ 
3   for  $i = 0$  to  $k-1$  do
4      $s[i] \leftarrow i$ 
5   end
6   for  $i = k$  to  $n-1$  do
7      $j \leftarrow \text{Rand}(i+1)$ 
8     if  $j < k$  then
9        $s[j] \leftarrow i$ 
10    end
11  end
12  return  $s$ 
13 end
14
15 function PoolSample( $n, k$ )
16   $s \leftarrow$  an array of length  $k$ 
17   $t \leftarrow$  an array of length  $n$ 
18  for  $i = 0$  to  $n-1$  do
19     $t[i] \leftarrow i$ 
20  end
21   $m \leftarrow n$ 
22  for  $i = 0$  to  $k-1$  do
23     $j \leftarrow \text{Rand}(m)$ 
24     $s[i] \leftarrow t[j]$ 
25     $m \leftarrow m-1$ 
26     $t[j] \leftarrow t[m]$ 
27  end
28  return  $s$ 
29 end
30
31 function InsertionSample( $n, k$ )
32   $s \leftarrow$  an array of length  $k$ 
33  for  $i = 0$  to  $k-1$  do
34     $v \leftarrow \text{Rand}(n-i)$ 
35     $j \leftarrow k-i$ 
36    while  $j < k$  and  $v \geq s[j]$  do
37       $v \leftarrow v+1$ 
38       $s[j-1] \leftarrow s[j]$ 
39       $j \leftarrow j+1$ 
40    end
41     $s[j-1] \leftarrow v$ 
42  end
43  return  $s$ 
44 end

```

Algorithm 2: Random sampling component algorithms.

pling algorithms for explanations for why each works. Our composition (Algorithm 1) chooses from among the three sampling algorithms (Algorithm 2) the one that requires the least random number generation for the given  $n$  and  $k$ . The runtime of reservoir sampling and pool sampling is  $O(n)$ , while the runtime of insertion sampling is  $O(k^2)$ . Pool sampling and inser-

```

1 function SimpleBitmask( $n, p$ )
2    $v \leftarrow$  an all 0 bit-vector of length  $n$ 
3   for  $i = 0$  to  $n - 1$  do
4     if  $\text{Rand}(0.0, 1.0) < p$  then
5        $\text{FlipBit}(v, i)$ 
6     end
7   end
8   return  $v$ 
9 end
10
11 function OptimizedBitmask( $n, p$ )
12    $v \leftarrow$  an all 0 bit-vector of length  $n$ 
13    $k \leftarrow B(n, p)$ 
14    $\text{indexes} \leftarrow \text{Sample}(n, k)$ 
15   for  $i \in \text{indexes}$  do
16      $\text{FlipBit}(v, i)$ 
17   end
18   return  $v$ 
19 end

```

Algorithm 3: Simple vs optimized bitmask creation.

tion sampling each generate  $k$  random integers, while reservoir sampling requires  $(n - k)$  random integers. The runtime of the composite of these algorithms is  $O(\min(n, k^2))$ , and requires  $\min(k, n - k)$  random integers (Cicirello, 2022a). Minimizing random number generation is perhaps even more important than runtime complexity, because although it is a constant time operation, random number generation is costly.

### 3.3 Optimizing Random Bitmasks

Our algorithms for mutation and crossover rely on random bitmasks of length  $n$  for probability  $p$  that a bit is a 1. Algorithm 3 compares pseudocode for the simple approach and the optimized binomial approach. The runtime (worst, average, and best cases) of the simple approach,  $\text{SimpleBitmask}(n, p)$ , is  $O(n)$ . The runtime of the optimized version,  $\text{OptimizedBitmask}(n, p)$ , is likewise  $O(n)$ , but the only  $O(n)$  step initializes an all zero bit-vector in line 12. Most of the cost savings is due to requiring only  $O(n \cdot \min(p, 1 - p))$  random numbers on average (the call to  $\text{Sample}()$  on line 14), compared to  $\text{SimpleBitmask}(n, p)$ , which always requires  $n$  random numbers. When  $p$  is small, such as for mutation where  $p$  is the mutation rate  $p_m$ , the cost savings from minimizing random number generation is especially advantageous as we will see in the experiments.

Not shown in Algorithm 3 for presentation clarity, our implementation of  $\text{OptimizedBitmask}(n, p)$  treats  $p = 0.5$  as a special case by generating 32 random bits at a time with uniformly distributed random 32-bit integers. The  $\text{OptimizedBitmask}(n, p)$ , as

```

1 function SimpleMutation( $v, p_m$ )
2    $n \leftarrow \text{Length}(v)$ 
3   for  $i = 0$  to  $n - 1$  do
4     if  $\text{Rand}(0.0, 1.0) < p_m$  then
5        $\text{FlipBit}(v, i)$ 
6     end
7   end
8 end
9
10 function OptimizedMutation( $v, p_m$ )
11    $n \leftarrow \text{Length}(v)$ 
12    $\text{bitmask} \leftarrow \text{OptimizedBitmask}(n, p_m)$ 
13    $v \leftarrow v \oplus \text{bitmask}$ 
14 end

```

Algorithm 4: Simple vs optimized mutation.

presented in Algorithm 3, requires  $\frac{n}{2}$  random bounded integers when  $p = 0.5$ , while this special case treatment reduces this to  $\frac{n}{32}$  random integers.

### 3.4 Optimizing Mutation

Algorithm 4 compares the common approach to mutation and our optimized approach. The  $p_m$  is mutation rate. Since the simple approach,  $\text{SimpleMutation}(v, p_m)$ , iterates over all  $n$  bits, generating one random number for each, its runtime is  $O(n)$ . The runtime of  $\text{OptimizedMutation}(v, p_m)$  is likewise  $O(n)$  due to the  $\oplus$  of vectors of length  $n$ , and the initialization of an all zero vector of length  $n$ . It is possible to eliminate these  $O(n)$  steps with explicit iteration over only the mutated bits instead of using a bitmask. However, these steps are relatively inexpensive given the implicit parallelism associated with utilizing 32-bit integers (e.g., bit operations on 32 bits at a time). The real time savings comes from reducing random number generation, where  $\text{OptimizedMutation}(v, p_m)$  requires only  $O(n \cdot \min(p_m, 1 - p_m))$  random numbers on average via the call to  $\text{OptimizedBitmask}(n, p_m)$  in line 12, while  $\text{SimpleMutation}(v, p_m)$  requires  $n$ . Since the mutation rate  $p_m$  is generally quite small,  $\text{OptimizedMutation}(v, p_m)$  eliminates nearly all random number generation.

### 3.5 Optimizing Uniform Crossover

Algorithm 5 compares the simple uniform crossover, determining the bits to exchange with iteration, versus our optimized version using our binomial trick. The  $p_u$  is uniform crossover's parameter for the per-bit probability of bit exchange. Both versions are identical aside from how they generate a random bitmask. The runtime of both is  $O(n)$  due to the bitwise operations. The time savings for

```

1 function SimpleCrossover( $v_1, v_2, p_u$ )
2    $n \leftarrow \text{Length}(v_1)$ 
3   bitmask  $\leftarrow \text{SimpleBitmask}(n, p_u)$ 
4   temp  $\leftarrow (v_1 \wedge \text{bitmask}) \vee (v_2 \wedge \neg \text{bitmask})$ 
5    $v_1 \leftarrow (v_2 \wedge \text{bitmask}) \vee (v_1 \wedge \neg \text{bitmask})$ 
6    $v_2 \leftarrow \text{temp}$ 
7 end
8
9 function OptimizedCrossover( $v_1, v_2, p_u$ )
10   $n \leftarrow \text{Length}(v_1)$ 
11  bitmask  $\leftarrow \text{OptimizedBitmask}(n, p_u)$ 
12  temp  $\leftarrow (v_1 \wedge \text{bitmask}) \vee (v_2 \wedge \neg \text{bitmask})$ 
13   $v_1 \leftarrow (v_2 \wedge \text{bitmask}) \vee (v_1 \wedge \neg \text{bitmask})$ 
14   $v_2 \leftarrow \text{temp}$ 
15 end

```

Algorithm 5: Simple vs optimized uniform crossover.

OptimizedCrossover( $v_1, v_2, p_u$ ) derives from optimizing bitmask creation in line 11, leading the optimized uniform crossover to require  $O(n \cdot \min(p_u, 1 - p_u))$  random numbers, rather than the  $O(n)$  random numbers required by the simple approach. For example, if  $p_u = 0.33$  or  $p_u = 0.67$ , then the optimization requires only a third of the random numbers that would be needed if explicit bit iteration was used.

### 3.6 Optimizing a Generation

Algorithm 6 compares a simple implementation of a generation with an optimized version. The SimpleGeneration() explicitly iterates over the  $\frac{n}{2}$  pairs of possible parents (lines 4–9), generating a uniform random variate for each to determine which parents produce offspring. The OptimizedGeneration() generates a single binomial random variate from  $B(\lfloor \frac{n}{2} \rfloor, p_c)$ , where  $p_c$  is the crossover rate, to determine the number of crossover applications (line 18), and then iterates without need for additional random numbers (lines 19–21).

Although the BTPE algorithm (Kachitvichyanukul and Schmeiser, 1988) that we use to generate binomial random variates utilizes rejection sampling (Flury, 1990), the average number of rejection sampling iterations is constant, and thus the average number of uniform variates needed by BTPE to generate a binomial is also constant (Cicirello, 2024b). While SimpleGeneration() requires  $O(\frac{n}{2})$  uniform random variates, OptimizedGeneration() requires only  $O(1)$  random numbers.

The OptimizedMutation() leads to additional speed advantage. The pseudocode uses a generic Crossover() operation rather than assuming any specific operator. In the experiments, we consider both uniform crossover, which we optimize, as

```

1 function SimpleGeneration( $\text{pop}, p_c, p_m$ )
2    $n \leftarrow \text{Length}(\text{pop})$ 
3   pop  $\leftarrow \text{Selection}(\text{pop})$ 
4   /* assume new population pop in
   random order */
5   pairs  $\leftarrow \lfloor \frac{n}{2} \rfloor$ 
6   for  $i = 0$  to pairs  $- 1$  do
7     if Rand(0.0, 1.0)  $< p_c$  then
8       | Crossover(pop $i$ , pop $i+\text{pairs}$ )
9     end
10  for  $i = 0$  to  $n - 1$  do
11    | SimpleMutation(pop $i$ ,  $p_m$ )
12  end
13 end
14
15 function OptimizedGeneration( $\text{pop}, p_c,$ 
     $p_m$ )
16   $n \leftarrow \text{Length}(\text{pop})$ 
17  pop  $\leftarrow \text{Selection}(\text{pop})$ 
18  /* assume new population pop in
  random order */
19  pairs  $\leftarrow B(\lfloor \frac{n}{2} \rfloor, p_c)$ 
20  for  $i = 0$  to pairs  $- 1$  do
21    | Crossover(pop $i$ , pop $i+\text{pairs}$ )
22  end
23  for  $i = 0$  to  $n - 1$  do
24    | OptimizedMutation(pop $i$ ,  $p_m$ )
25  end

```

Algorithm 6: Simple vs optimized generation.

well as single-point and two-point crossover, which don't have corresponding binomial optimizations. The cross points of our single-point and two-point crossover operators are selected using a more efficient algorithm for bounded random integers (Lemire, 2019) than Java's built-in method; and the pair of indexes for two-point crossover are sampled using a specially designed algorithm for small random samples (Cicirello, 2024a) that is significantly faster than general purpose sampling algorithms such as those utilized earlier in Section 3.2. However, the experiments in this paper that use single-point and two-point crossover use these same optimizations for both the simple and optimized experimental conditions.

## 4 EXPERIMENTS

We run the experiments on a Windows 10 PC with an AMD A10-5700, 3.4 GHz processor and 8GB memory, and we use OpenJDK 64-Bit Server VM

Table 2: URLs for Chips-n-Salsa and experiments.

Chips-n-Salsa library	
Source	<a href="https://github.com/cicirello/Chips-n-Salsa">https://github.com/cicirello/Chips-n-Salsa</a>
Website	<a href="https://chips-n-salsa.cicirello.org/">https://chips-n-salsa.cicirello.org/</a>
Maven	<a href="https://central.sonatype.com/artifact/org.cicirello/chips-n-salsa">https://central.sonatype.com/artifact/org.cicirello/chips-n-salsa</a>
Experiments	
Source	<a href="https://github.com/cicirello/optimize-ga-operators">https://github.com/cicirello/optimize-ga-operators</a>

Table 3: CPU time for  $10^5$  mutations for  $n = 1024$ .

$p_m$	CPU time (seconds)		% less time	t-test $p$ -value
	simple	optimized		
1/1024	0.856	0.00906	98.9%	$\sim 0.0$
1/512	0.857	0.0119	98.6%	$\sim 0.0$
1/256	0.860	0.0173	98.0%	$\sim 0.0$
1/128	0.866	0.0300	96.5%	$< 10^{-291}$
1/64	0.877	0.0642	92.7%	$\sim 0.0$
1/32	0.899	0.140	84.5%	$< 10^{-285}$
1/16	0.946	0.192	79.7%	$< 10^{-321}$
1/8	1.05	0.255	75.7%	$< 10^{-193}$
1/4	1.25	0.363	71.0%	$\sim 0.0$

version 17.0.2. We implemented the optimized bit-flip mutation, uniform crossover, and generation loop within the open source library Chips-n-Salsa (Cicirello, 2020), and use version 7.0.0 in the experiments. All experiment source code is also open source. Table 2 provides the relevant URLs.

The remainder of this section is organized as follows. Sections 4.1 and 4.2 present our experiments with mutation and uniform crossover, respectively. Then, in Section 4.3, we provide experiments comparing a fully optimized GA that optimizes the choice of which pairs of parents to cross in addition to the mutation and uniform crossover optimizations.

#### 4.1 Mutation Experiments

In our mutation experiments, we consider bit-vector length  $n \in \{16, 32, 64, 128, 256, 512, 1024\}$ , and mutation rate  $p_m \in \{\frac{1}{n}, \frac{2}{n}, \dots, \frac{1}{4}\}$ . For each combination  $(n, p_m)$ , we measure the CPU time to perform 100,000 mutations, averaged across 100 trials. We test the significance of the differences between the simple and optimized versions using Welch’s unequal variances t-test (Welch, 1947; Derrick and White, 2016).

Figure 1 visualizes  $n \in \{16, 64, 256, 1024\}$ . Table 3 summarizes results for  $n = 1024$ . Data for all other cases is found in the GitHub repository, and is similar to the cases presented here.

The optimized mutation leads to massive performance gains. For bit-vector length  $n = 1024$ , the optimized mutation uses 71% less time for high mutation

Table 4: CPU time for  $10^5$  uniform crosses for  $n = 1024$ .

$p_u$	CPU time (seconds)		% less time	t-test $p$ -value
	simple	optimized		
0.1	0.962	0.245	74.6%	$\sim 0.0$
0.2	1.13	0.355	68.5%	$\sim 0.0$
0.3	1.31	0.471	64.0%	$< 10^{-308}$
0.4	1.50	0.577	61.6%	$< 10^{-312}$
0.5	1.62	0.0142	99.1%	$\sim 0.0$

rates. For typical low mutation rates, the optimized mutation uses 96%–99% less time than the simple implementation. All results are extremely statistically significant with t-test  $p$ -values very near zero.

#### 4.2 Uniform Crossover Experiments

We use the same bit-vector lengths  $n$  for the crossover experiments as we did for the mutation experiments; and we consider  $p_u \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$  for the per-bit probability of an exchange between parents. We do not consider  $p_u > 0.5$  because any such  $p_u$  has an equivalent counterpart  $p_u < 0.5$  (e.g., exchanging 75% of the bits between the parents leads to the same children as if we instead exchanged the other 25% of the bits). For each combination  $(n, p_u)$ , we measure the CPU time to perform 100,000 uniform crossovers, averaged across 100 trials, and again test significance with Welch’s unequal variances t-test.

Figure 2 visualizes  $n \in \{16, 64, 256, 1024\}$ . Table 4 summarizes results for  $n = 1024$ . The data for all other cases is found in the GitHub repository, and is similar to the cases presented here.

The optimized uniform crossover leads to similar performance gains as seen with mutation. Specifically, for bit-vector length  $n = 1024$ , the optimized uniform crossover uses approximately 60% to 75% less time than the simple implementation, except for the case of  $p_u = 0.5$  where the optimized version uses 99% less time. The performance of  $p_u = 0.5$  is especially strong due to our special case treatment when generating random bitmasks (see earlier discussion in Section 3). All results are extremely statistically significant with t-test  $p$ -values very near zero.

#### 4.3 GA Experiments

Unlike mutation and crossover, it is not feasible to isolate the generation control logic of Algorithm 6 from the GA as it depends upon the genetic operators. Instead we experiment with a GA with simple vs optimized operators. We use the OneMax problem (Ackley, 1985) for its simplicity since our focus is on runtime performance of alternative implementations of operators, and use vector length  $n = 1024$

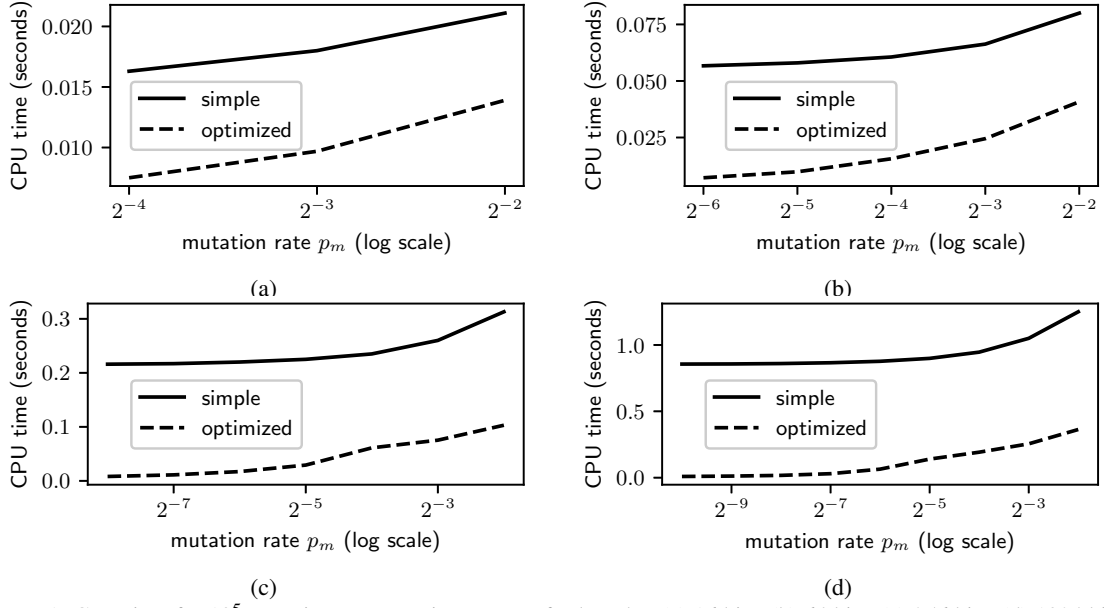


Figure 1: CPU time for  $10^5$  mutations vs mutation rate  $p_m$  for lengths: (a) 16 bits, (b) 64 bits, (c) 256 bits, (d) 1024 bits.

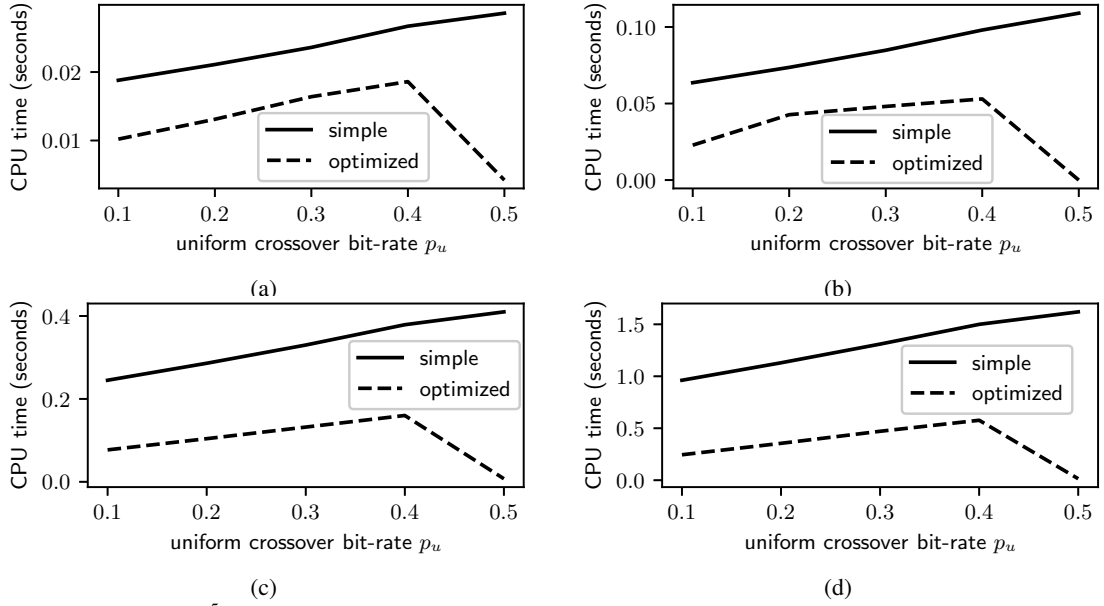


Figure 2: CPU time for  $10^5$  uniform crosses vs uniform rate  $p_u$  for lengths: (a) 16 bits, (b) 64 bits, (c) 256 bits, (d) 1024 bits.

bits. All experimental conditions use population size 100, stochastic universal sampling (Baker, 1987) for selection, and mutation rate  $p_m = \frac{1}{1024}$ , which leads to an expected one mutated bit per population member per generation. We consider crossover rates  $p_c \in \{0.05, 0.15, \dots, 0.95\}$ . Each GA run is 1000 generations, and we average results over 100 trials. We test significance with Welch's unequal variances t-test.

We consider four cases. Case (a) compares the simple versions of the generation logic, mutation, and uniform crossover ( $p_u = 0.33$ ) versus the optimized

versions of these. Case (b) is similar, but with uniform crossover parameter  $p_u = 0.49$ . We decided not to use  $p_u = 0.5$  to avoid the extra strong performance of our optimized bitmask generation for that special case. Cases (c) and (d) are as the others, but with single-point and two-point crossover, respectively.

Table 5 shows the results for case (a) uniform crossover ( $p_u = 0.33$ ). The optimized approach uses from approximately 81% less time for a high crossover rate ( $p_c = 0.95$ ) to 95% less time for a low crossover rate ( $p_c = 0.05$ ). The runtime differ-

Table 5: CPU time and average solution of 1024-bit OneMax using 1000 generations with uniform crossover ( $p_u = 0.33$ ).

$p_c$	CPU time (seconds)		% less time	t-test $p$ -value	average solution		t-test $p$ -value
	simple	optimized			simple	optimized	
0.05	0.869	0.0423	95.1%	$\sim 0.0$	687.33	686.57	0.541
0.15	0.942	0.0698	92.6%	$< 10^{-279}$	709.20	709.88	0.611
0.25	1.01	0.0950	90.6%	$< 10^{-259}$	715.94	714.62	0.328
0.35	1.07	0.121	88.7%	$\sim 0.0$	719.01	719.64	0.639
0.45	1.14	0.148	87.0%	$< 10^{-314}$	720.77	721.57	0.512
0.55	1.21	0.174	85.6%	$\sim 0.0$	721.54	722.01	0.718
0.65	1.27	0.200	84.3%	$\sim 0.0$	722.97	724.94	0.158
0.75	1.34	0.224	83.3%	$\sim 0.0$	723.89	722.16	0.163
0.85	1.41	0.252	82.1%	$\sim 0.0$	725.60	726.18	0.655
0.95	1.47	0.277	81.2%	$\sim 0.0$	724.62	724.73	0.929

Table 6: CPU time and average solution of 1024-bit OneMax using 1000 generations with uniform crossover ( $p_u = 0.49$ ).

$p_c$	CPU time (seconds)		% less time	t-test $p$ -value	average solution		t-test $p$ -value
	simple	optimized			simple	optimized	
0.05	0.875	0.0467	94.7%	$\sim 0.0$	690.05	689.17	0.454
0.15	0.956	0.0803	91.6%	$< 10^{-312}$	711.34	712.19	0.572
0.25	1.03	0.114	88.9%	$\sim 0.0$	717.99	717.08	0.439
0.35	1.11	0.148	86.7%	$\sim 0.0$	720.71	722.44	0.162
0.45	1.19	0.182	84.8%	$\sim 0.0$	722.24	720.16	0.102
0.55	1.27	0.216	83.0%	$\sim 0.0$	723.10	723.38	0.826
0.65	1.35	0.250	81.5%	$\sim 0.0$	723.67	724.12	0.707
0.75	1.43	0.283	80.2%	$\sim 0.0$	725.33	724.64	0.582
0.85	1.51	0.318	79.0%	$\sim 0.0$	725.65	724.22	0.272
0.95	1.59	0.352	77.9%	$\sim 0.0$	724.85	724.44	0.761

Table 7: CPU time and average solution of 1024-bit OneMax using 1000 generations with single-point crossover.

$p_c$	CPU time (seconds)		% less time	t-test $p$ -value	average solution		t-test $p$ -value
	simple	optimized			simple	optimized	
0.05	0.836	0.0283	96.6%	$\sim 0.0$	659.20	659.51	0.798
0.15	0.838	0.0286	96.6%	$\sim 0.0$	683.32	684.49	0.342
0.25	0.839	0.0306	96.4%	$< 10^{-260}$	693.77	694.79	0.413
0.35	0.840	0.0308	96.3%	$\sim 0.0$	701.48	703.06	0.230
0.45	0.839	0.0325	96.1%	$< 10^{-321}$	706.65	705.55	0.334
0.55	0.842	0.0323	96.2%	$\sim 0.0$	709.60	708.17	0.265
0.65	0.843	0.0342	95.9%	$\sim 0.0$	711.61	710.39	0.321
0.75	0.843	0.0355	95.8%	$< 10^{-310}$	713.20	713.91	0.571
0.85	0.843	0.0366	95.7%	$< 10^{-269}$	715.36	716.18	0.503
0.95	0.850	0.0373	95.6%	$< 10^{-223}$	716.60	716.36	0.854

ences are extremely statistically significant with t-test  $p$ -values near 0.0.

Table 6 provides detailed results for case (b) uniform crossover ( $p_u = 0.49$ ). The results follow the same trend as the previous case. The approach optimized using the binomial distribution uses from approximately 78% less time for a high crossover rate ( $p_c = 0.95$ ) to 95% less time for a low crossover rate ( $p_c = 0.05$ ). The runtime differences are extremely statistically significant with t-test  $p$ -values near 0.0.

Table 7 summarizes the results for case (c) single-

point crossover. Unlike uniform crossover, the speed difference does not vary by crossover rate. Instead, the optimized approach uses approximately 95% to 97% less time than the simple GA implementation for all crossover rates. All runtime differences are extremely statistically significant with all t-test  $p$ -values very near 0.0.

Table 8 summarizes the results for case (d) two-point crossover. The trend is the same as in the case of single-point crossover. The binomially optimized approach uses approximately 95% to 97% less time



Table 8: CPU time and average solution of 1024-bit OneMax using 1000 generations with two-point crossover.

$p_c$	CPU time (seconds)		% less time	t-test $p$ -value	average solution		t-test $p$ -value
	simple	optimized			simple	optimized	
0.05	0.840	0.0291	96.5%	$< 10^{-316}$	666.82	666.08	0.526
0.15	0.840	0.0292	96.5%	$\sim 0.0$	692.26	692.32	0.959
0.25	0.839	0.0306	96.4%	$< 10^{-296}$	702.23	703.29	0.394
0.35	0.841	0.0313	96.3%	$\sim 0.0$	708.16	709.99	0.124
0.45	0.841	0.0333	96.0%	$< 10^{-301}$	712.22	712.39	0.897
0.55	0.842	0.0338	96.0%	$\sim 0.0$	714.05	713.80	0.845
0.65	0.844	0.0347	95.9%	$< 10^{-311}$	718.86	715.63	0.00829
0.75	0.845	0.0364	95.7%	$\sim 0.0$	718.60	717.78	0.504
0.85	0.845	0.0377	95.5%	$< 10^{-318}$	719.54	718.86	0.611
0.95	0.846	0.0383	95.5%	$\sim 0.0$	720.30	721.55	0.320

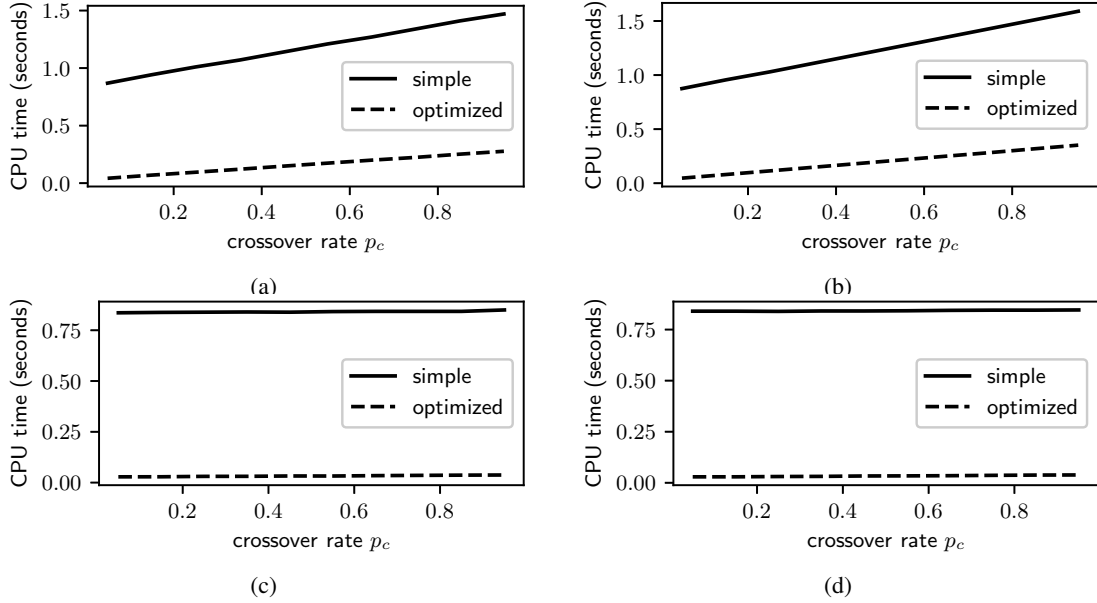


Figure 3: CPU time for 1024-bit OneMax using 1000 generations with population size 100 vs crossover rate  $p_c$  for crossover operators: (a) uniform ( $p_u = 0.33$ ), (b) uniform ( $p_u = 0.49$ ), (c) single-point, (d) two-point.

than the basic implementation, and does not vary by crossover rate. All runtime differences are extremely statistically significant with all t-test  $p$ -values very near 0.0.

Tables 5, 6, 7, and 8 also show average OneMax solutions (i.e., number of 1-bits) to demonstrate that the optimized approach does not statistically alter GA problem-solving behavior. For any given crossover operator and crossover rate  $p_c$ , there is no statistical significance in solution quality between the optimized and simple approach (i.e., high  $p$ -values).

Figure 3 visualizes the results for all four cases. When uniform crossover is used, runtime increases with crossover rate. The graphs appear to show constant runtime when either single-point (Figure 3c) or two-point crossover (Figure 3d) is used. However, runtime is increasing in these cases, just very slowly

as seen in the detailed results from Tables 7 and 8. The performance differential between the simple and optimized approaches doesn't vary by crossover rate when single-point (Figure 3c) or two-point crossover (Figure 3d) are used, with the optimized approach consistently using 95% less time; while the performance differential between the optimized and simple approaches does vary with crossover rate when uniform crossover is used (Figures 3a and 3b).

## 5 CONCLUSION

In this paper, we demonstrated how we can significantly speed up the runtime of some GA operators, including the common bit-flip mutation and uniform crossover, by observing that such operators define bi-

nomial experiments (i.e., sequence of Bernoulli trials). This enables replacing explicit iteration that generates a random floating-point value for each bit to determine whether to flip (for mutation) or exchange (for crossover), with the generation of a single binomial random variate to determine the number of bits  $k$ , and an efficient sampling algorithm to choose the  $k$  bits to mutate or cross. As a consequence, costly random number generation is significantly reduced. A similar approach is also seen for the generation logic that determines the number of parents to cross.

The technique is not limited to these operators, and is applicable for any operator that is controlled by some probability  $p$  of including an element in the mutation or cross. For example, several evolutionary operators for permutations (Cicirello, 2023) operate in this way, including uniform order based crossover (Syswerda, 1991), order crossover 2 (Syswerda, 1991; Starkweather et al., 1991), uniform partially matched crossover (Cicirello and Smith, 2000), uniform scramble mutation (Cicirello, 2023), and uniform precedence preservative crossover (Bierwirth et al., 1996). We adapt this approach in our implementations of all of these evolutionary permutation operators in the open source library Chips-n-Salsa (Cicirello, 2020).

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