

# Efficient Simulation Of A Simple Evolutionary System

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# Outline

Background

Question 1: Convergence of finite population

Question 2: Finite population oscillation

Question 3: Finite population oscillation under mutation-violation

Question 4: Finite population oscillation under crossover-violation

Conclusion

# Terms

Population  $P$ : a collection of length  $\ell$  binary strings

Population vector:  $\mathbf{p}_j$  proportion of string  $j$  in the population

If  $P = 00, 01, 01, 10, 11, 11$ , then  $\mathbf{p}_3 = 2/6 = 1/3$

$\mathcal{R}$  denotes the set of binary strings of length  $\ell$ ,  $|\mathcal{R}| = Z = 2^\ell$

Addition and multiplication of elements in  $\mathcal{R}$  are bitwise operations modulo 2

$$x = 1101, y = 1010$$

$$x + y = 1101 + 1010 = 0111$$

$$xy = 1101 \cdot 1010 = 1000$$

$$\bar{x} = 0010$$

## Crossover & Mutation

Crossover : Choose parents  $u$  and  $v$ , exchange bits using crossover mask  $m$ :

$$u' = um + v\bar{m}, v' = u\bar{m} + vm$$

$$u = \mathbf{1100}, v = 1101, m = 1100$$

$$\{\mathbf{1100}, 1101\} \rightarrow \{\mathbf{1100} + 0001, 0000 + 1100\} \rightarrow \{\mathbf{1101}, \mathbf{1100}\}$$

$\chi_m$  = probability of using crossover mask  $m$

Mutation: Flip bits using mutation mask:

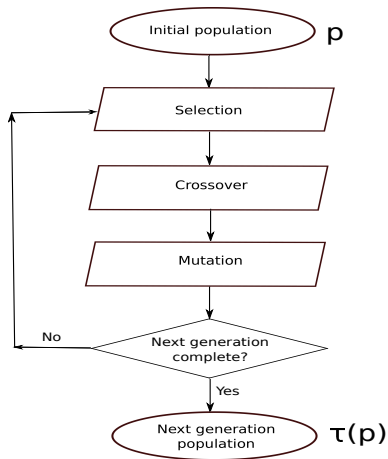
$$x \rightarrow x + m$$

$$x = 1100, m = 0001$$

$$1100 \rightarrow 1100 + 0001 \rightarrow 1101$$

$\mu_m$  = probability of using mutation mask  $m$

# Finite Population GA



Randomly select parents  $u$  and  $v$

Crossover  $u$  and  $v$  to produce  $u'$  and  $v'$

Keep one of  $u'$ ,  $v'$ , and mutate to produce gamete  $g$

Repeat above to form next generation

# Random Heuristic Search

$\tau$  is a stochastic transition rule that maps  $\mathbf{p}$  to

$$\mathbf{p}' \in \Lambda_N = \{ \langle \frac{X_1}{N}, \dots, \frac{X_Z}{N} \rangle \mid X_i \in \mathbb{Z}^{\geq 0}, \sum X_i = N \}$$

$\mathbf{p}, \tau(\mathbf{p}), \tau^2(\mathbf{p}), \dots$  forms Markov chain

$\tau(\mathbf{p})$  cannot be predicted with certainty

# Infinite Population Model

Population modeled as vector  $\mathbf{p} \in \Lambda = \{\langle \mathbf{p}_1, \dots, \mathbf{p}_Z \rangle \mid \mathbf{p}_i \geq 0, \sum \mathbf{p}_i = 1\}$

$\mathcal{G}$  maps  $\mathbf{p}$  to the next generation  $\mathbf{p}'$

$\mathcal{G}(\mathbf{p})_j =$  proportion of string  $j$  in the next generation

The infinite population model

$$\mathbf{p} \rightarrow \mathcal{G}(\mathbf{p}) \rightarrow \mathcal{G}(\mathcal{G}(\mathbf{p})) \rightarrow \dots$$

The variance is

$$\mathcal{E}(\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\|^2) = \frac{1 - \|\mathcal{G}(\mathbf{p})\|^2}{N}$$

## Question 1: Distance Between Finite and Infinite Population

Chebyshev's inequality:

$$\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\| \leq \frac{k}{\sqrt{N}}$$

Jensen's inequality:

$$\mathcal{E}(\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\|) \leq \frac{\sqrt{1 - \|\mathcal{G}(\mathbf{p})\|^2}}{\sqrt{N}}$$

Geometric point of view:

$$\sup_{\xi \in \Lambda} \inf_{\mathbf{p} \in \Lambda_N} \|\xi - \mathbf{p}\| = O(1/\sqrt{N})$$

Does the distance decrease in practice like  $1/\sqrt{N}$  ?



# Diploid Population Model

Diploid genome:  $\alpha = \langle \alpha_0, \alpha_1 \rangle$

Population vector  $\mathbf{q}_\alpha$  : prevalence of diploid  $\alpha$

$t_\alpha(g)$  : probability that gamete  $g$  is produced from parent  $\alpha$

$$\mathbf{q}'_\gamma = \sum_{\alpha} \mathbf{q}_\alpha t_\alpha(\gamma_0) \sum_{\beta} \mathbf{q}_\beta t_\beta(\gamma_1)$$

# Diploid Model Reduction to Haploid Model

Diploids in terms of haploids:

$$\mathbf{q}_{\langle\gamma_0, \gamma_1\rangle} = \mathbf{p}_{\gamma_0} \mathbf{p}_{\gamma_1}$$

Haploids in terms of diploids:

$$\mathbf{p}_g = \frac{1}{2} \sum_{\alpha_0, \alpha_1} \mathbf{q}_{\langle\alpha_0, \alpha_1\rangle} ([g = \alpha_0] + [g = \alpha_1])$$

Evolution equation in terms of haploid distribution  $\mathbf{p}$ :

$$\mathbf{p}'_{\gamma_0} = \sum_{\alpha_0, \alpha_1} \mathbf{p}_{\alpha_0} \mathbf{p}_{\alpha_1} t_{\langle\alpha_0, \alpha_1\rangle}(\gamma_0)$$

Matrix form:

$$\mathbf{p}'_g = \mathbf{p}^T M_g \mathbf{p} \quad \text{where} \quad (M_g)_{u,v} = t_{\langle u,v\rangle}(g)$$

## Specialization to Vose's Haploid Model

Mutation distribution:

$$\mu_i = (\mu)^{\mathbf{1}^T i} (1 - \mu)^{\ell - \mathbf{1}^T i}$$

Crossover distribution:

$$\chi_i = \begin{cases} \chi c_i & \text{if } i > 0 \\ 1 - \chi + \chi c_0 & \text{if } i = 0 \end{cases}$$

For uniform crossover,  $c_i = 2^{-\ell}$

$$t_{\langle u, v \rangle}(g) = \sum_{i \in \mathcal{R}} \sum_{j \in \mathcal{R}} \sum_{k \in \mathcal{R}} \mu_i \mu_j \frac{\chi_k + \chi_{\bar{k}}}{2} [k(u + i) + \bar{k}(v + j) = g]$$

## Walsh Basis

$$W_{n,t} = Z^{-1/2}(-1)^{n^T t} \text{ where } Z = 2^\ell$$

$$\hat{A} = WAW$$

$$\hat{w} = Ww$$

Mixing matrix in Walsh basis

$$\hat{M}_{u,v} = 2^{\ell-1} [uv = \mathbf{0}] \hat{\mu}_u \hat{\mu}_v \sum_{k \in \overline{u+v}\mathcal{R}} \chi_{k+u} + \chi_{k+v}$$

Evolution eqn in Walsh basis

$$\hat{\mathbf{p}}'_g = 2^{\ell/2} \sum_{i \in g\mathcal{R}} \hat{\mathbf{p}}_i \hat{\mathbf{p}}_{i+g} \hat{M}_{i,i+g} \quad \text{where } g\mathcal{R} = \{gi \mid i \in \mathcal{R}\}$$

# Computational Advantages

Reduction to haploid model and Walsh basis simplifiy computation, which otherwise for diploid case would have been impractical

Only one mixing matrix as opposed to  $2^\ell$  is needed to compute next generation

For  $\ell = 14$ , using  $2^{14}$  mixing matrices with each having  $2^{14} \cdot 2^{14}$  entries would require 32 TB of memory, whereas one mixing matrix requires only 2 GB

# Distance Computation

Naive implementation:

$$\|\mathbf{f} - \mathbf{q}\|^2 = \sum_{\alpha} (\mathbf{f}_{\alpha} - \mathbf{q}_{\alpha})^2 \longrightarrow 2^{\ell} \cdot 2^{\ell} \text{ terms}$$

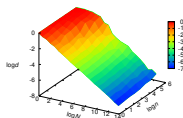
Our implementation:

$$S_{\mathbf{f}} = \{\alpha \mid \mathbf{f}_{\alpha} > 0\}$$

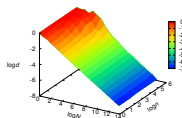
$$\|\mathbf{f} - \mathbf{q}\|^2 = \sum_g (\mathbf{p}_g)^2 + \sum_{\alpha \in S_{\mathbf{f}}} \mathbf{f}_{\alpha} (\mathbf{f}_{\alpha} - 2\mathbf{q}_{\alpha}) \rightarrow 2^{\ell} + |S_{\mathbf{f}}| \text{ terms}$$

# Convergence: Results

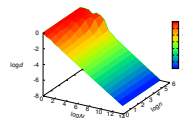
$$\chi = 0.1, \mu = 0.001$$



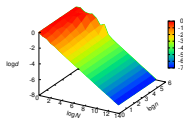
(a)  $\ell = 4$



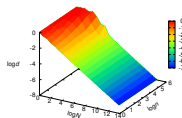
(b)  $\ell = 6$



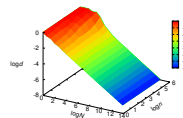
(c)  $\ell = 8$



(d)  $\ell = 10$



(e)  $\ell = 12$

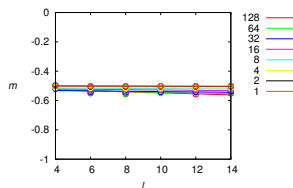


(f)  $\ell = 14$

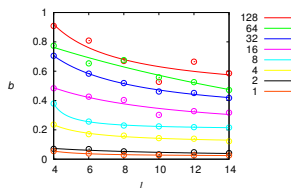
**Figure :** Convergence of finite population behaviour

# Regression

$$\log d = m \log N + b$$



(a) Slope  $m$



(b) Intercept  $b$

**Figure :** Regression parameter for generation  $n \in \{1, 2, 4, 8, 16, 32, 64, 128\}$

$$d \approx N^m e^b$$

From figure (a) above,  $m \approx -0.5$

$$d \approx k/\sqrt{N}$$



## Convergence: Conclusion

Does the distance between finite and infinite population decrease like  $1/\sqrt{N}$  ?

Yes

## Question 2

Finite Population Oscillation

# Limits

Infinite population evolution

$$\mathbf{p}, \mathcal{G}(\mathbf{p}), \mathcal{G}^2(\mathbf{p}), \dots$$

may converge to a fixed point

$$\mathcal{G}(\omega) = \lim_{n \rightarrow \infty} \mathcal{G}^n(\mathbf{p}) = \omega$$

But under some circumstances, evolution converges to a periodic orbit that oscillates between two fixed points,  $\mathbf{p}^*$  and  $\mathbf{q}^*$

# Periodic Orbit: Necessary and Sufficient Conditions

For some  $g \in \mathcal{R}, g \neq 0$

$$\begin{aligned}-1 &= \sum_j (-1)^{g^T j} \mu_j \\ 1 &= \sum_{k \in \bar{g}\mathcal{R}} \chi_{k+g} + \chi_k\end{aligned}$$

Infinite populations converge to a periodic orbit

Do finite populations also exhibit oscillation from random initial populations?

## Previous Works on Oscillation

Akin (1982) proved existence of cycling for continuous-time 2-bit diploid model

Hasting (1981) studied cycling in populations with infinite 2-bit diploid population model

Wright and Bidwell (1997) provided examples of cycling in an infinite haploid model with crossover and mutation for 3 bit and 4 bit populations

Wright and Agapie (2001) described cycling in infinite population for up to 4 bits, and also presented data for cycling in finite population

## Difference From Previous Works

Akin considers continuous time, we consider discrete time

Hastings' study is limited to two bits, and only crossover, no mutation

Wright and Bidwell consider for specific parameter values

Wright and Agapie use dynamic mutation

# Simulation

Simulations were run for both haploid and diploid populations

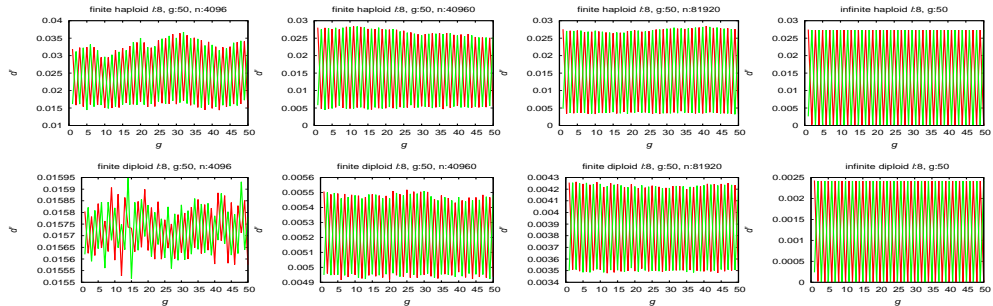
Random initial population

$$\ell \in \{8, 10, 12, 14\}$$

$$N \in \{4096, 40960, 81920\}$$

To visualize, distance of population to fixed points  $\mathbf{p}^*$  and  $\mathbf{q}^*$  is plotted

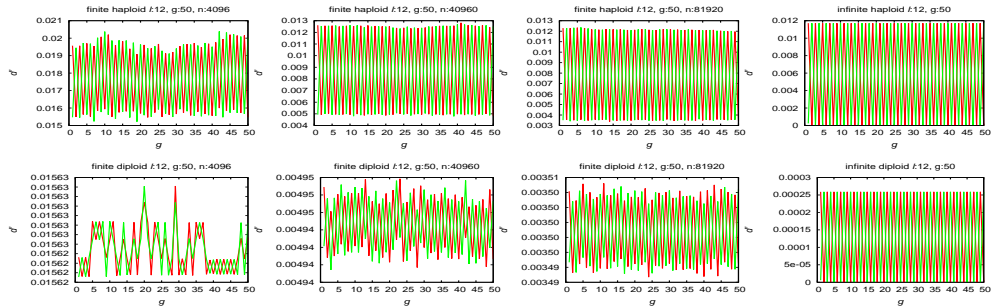
# Oscillation: Results



**Figure :** Infinite and finite population behavior for genome length  $\ell = 8$



# Oscillation: Results



**Figure :** Infinite and finite population behavior for genome length  $\ell = 12$

## Oscillation: Conclusion

Finite populations exhibit approximate oscillations

## Question 3

Oscillation Under Mutation-Violation

$$-1 \neq \sum_j (-1)^{g^T j} \mu_j$$

# Mutation-Violation

$$\mu_0 := \epsilon$$

$$\mu_i := (1 - \epsilon)\mu_i$$

This modification makes the Markov chain regular

No periodic orbits for finite population

No periodic orbits for infinite population

Can finite population exhibit approximate oscillations?

# Simulation

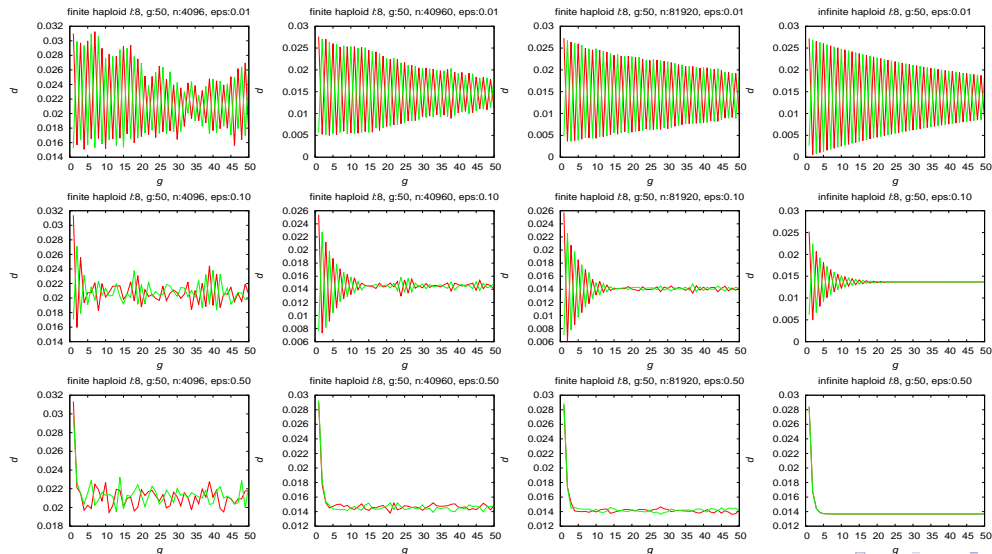
$$\epsilon \in \{0.01, 0.1, 0.5\}$$

$$\ell \in \{8, 10, 12, 14\}$$

$$N \in \{4096, 40960, 81920\}$$

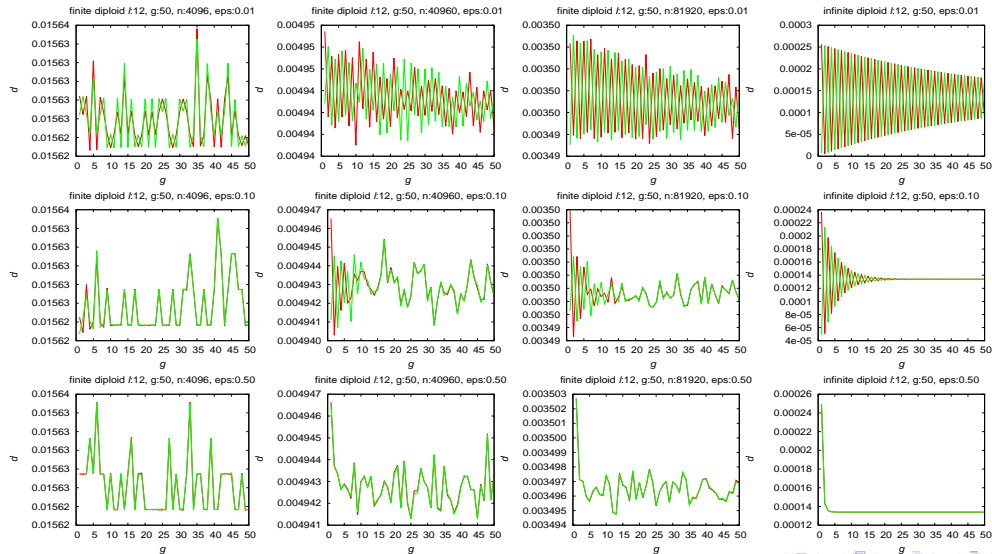
Distance to limits  $p^*$  and  $q^*$  without violation ( $\epsilon = 0$ ) are plotted

# Mutation-Violation: Results



**Figure :** Infinite and finite haploid population behavior for  $\mu$  violation and  $\ell = 8$

# Mutation-Violation: Results



**Figure :** Infinite and finite diploid population behavior for  $\mu$  violation and  $\ell = 12$

## Mutation-Violation: Conclusion

Approximate oscillation is exhibited when mutation-violation is small

If violation is large, then oscillation decreases

As string length increases, oscillation degrades



## Question 4

Oscillation under Crossover-Violation

$$1 \neq \sum_{k \in \bar{g}\mathcal{R}} \chi_{k+g} + \chi_k$$

# Crossover-Violation

$$\chi_i := (1 - \epsilon)\chi_i$$

$$\chi_j := \epsilon \quad j \text{ is chosen where } \chi_j = 0$$

No periodic orbit exists for infinite population

Can finite populations exhibit approximate oscillation?

# Simulation

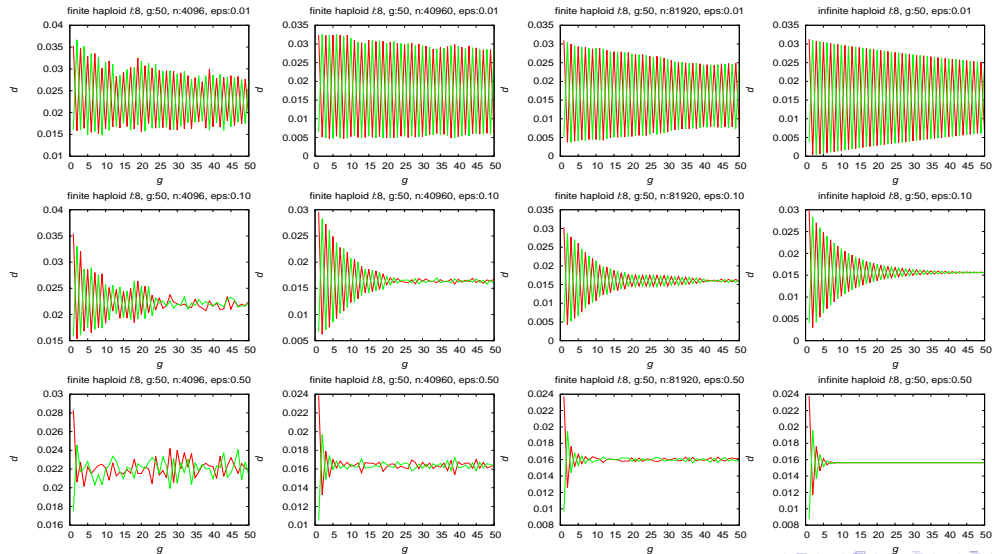
$$\epsilon = \{0.01, 0.1, 0.5\}$$

$$\ell = \{8, 10, 12, 14\}$$

$$N = \{4096, 40960, 81920\}$$

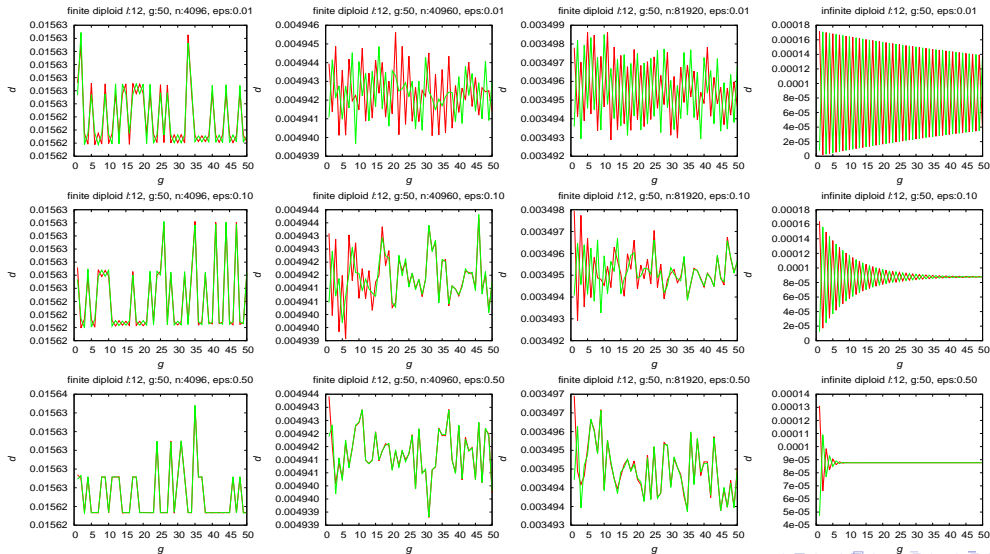
Distance to limits  $\mathbf{p}^*$  and  $\mathbf{q}^*$  without violation ( $\epsilon = 0$ ) are plotted

# Crossover-Violation: Results



**Figure :** Infinite and finite haploid population behavior for  $\chi$  violation and  $\ell = 8$

# Crossover-Violation: Results



**Figure :** Infinite and finite diploid population behavior for  $\chi$  violation and  $\ell = 12$

## Crossover-Violation: Conclusion

Approximate oscillation is exhibited when crossover-violation is small

If violation is large, then oscillation decreases

More randomness is observed with violation in crossover than in mutation

Randomness increases as string length increases

# Conclusion

Vose's haploid model makes computation efficient in diploid case by reducing to haploid case

Distance between finite population and infinite population can decrease like  $1/\sqrt{N}$

When infinite populations oscillate, finite populations exhibit approximate oscillation

Markov chain is regular under mutation-violation; finite populations exhibit approximate oscillation for small violation

Finite populations exhibit approximate oscillation for small crossover-violation

Thank You!!

Questions?





## Chebyshev's Inequality

Let  $\epsilon = f(r)/\sqrt{r}$ , where  $f(r)$  grows arbitrarily slowly such that

$$\lim_{r \rightarrow \infty} f(r) = \infty$$

and

$$\lim_{r \rightarrow \infty} f(r)/\sqrt{r} = 0.$$

From Chebyshev's inequality,

$$\lim_{r \rightarrow \infty} P(\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\| \geq \epsilon) \leq \lim_{r \rightarrow \infty} \frac{1 - \|\mathcal{G}(\mathbf{p})\|^2}{f(r)^2} = 0$$

This suggests the distance between  $\tau(\mathbf{p})$  and  $\mathcal{G}(\mathbf{p})$  might decrease as  $1/\sqrt{r}$

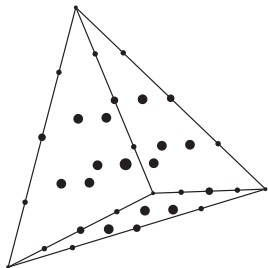
## Jensen's Inequality

Let  $\eta$  be the random variable  $\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\|$ , and convex function be  $\phi(x) = x^2$   
Then from Jensen's Inequality,

$$\mathcal{E}(\|\tau(\mathbf{p}) - \mathcal{G}(\mathbf{p})\|) = \mathcal{E}(\eta) \leq \sqrt{\mathcal{E}(\eta^2)} = \frac{\sqrt{1 - \|\mathcal{G}(\mathbf{p})\|^2}}{\sqrt{r}}$$

This also suggests the distance might decrease as  $1/\sqrt{r}$

# Population Points



Finite populations are represented by dots

Infinite population can be anywhere in the space

Distance between a finite population and an infinite population is  $O(1/\sqrt{r})$

This suggests the distance between  $\tau(\mathbf{p})$  and  $\mathcal{G}(\mathbf{p})$  might decrease as  $1/\sqrt{r}$

# History

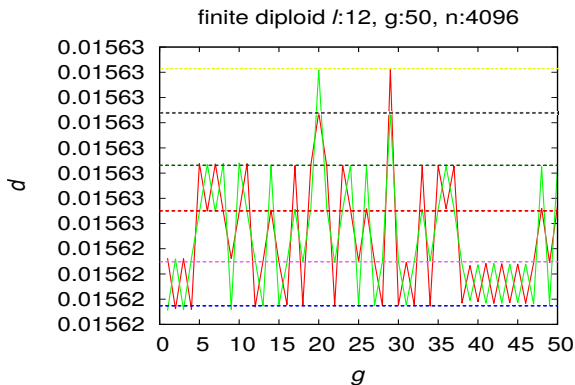
Haldane, in 1932, summarized basic population genetics models : Wright, Fisher and Haldane

Several people working with evolution-inspired algorithms in the 1950s and the 1960s Box (1957), Friedman(1959), Bledsoe (1961), Bremermann (1962), and Reed, Toombs and Baricelli (1967)

In 1960s and 1970s, Holland and colleagues formalized and promoted population based algorithms with crossover and mutation

Vose (1999) presented efficient methods for computing with a haploid model using mask-based operators introduced by Geiringer (1944)

## Oscillation: Unusual Behavior

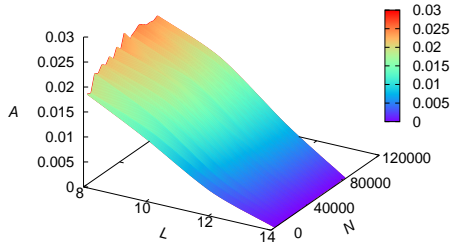


(a)

**Figure :** Oscillation between different points

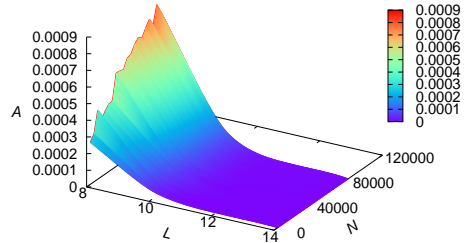
# Oscillation Amplitude

Average oscillation amplitude (haploid)



(a)

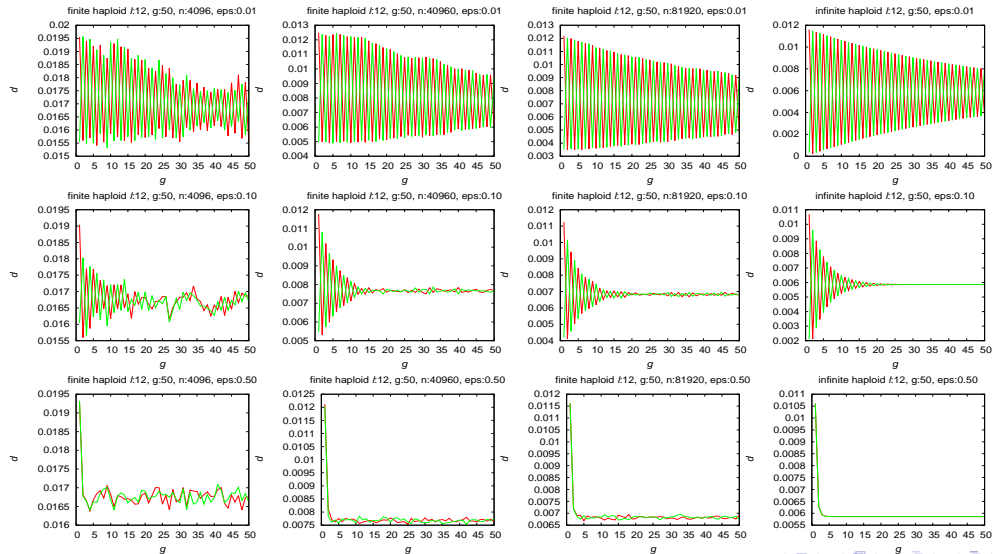
Average oscillation amplitude (diploid)



(b)

**Figure :** Average oscillation amplitude

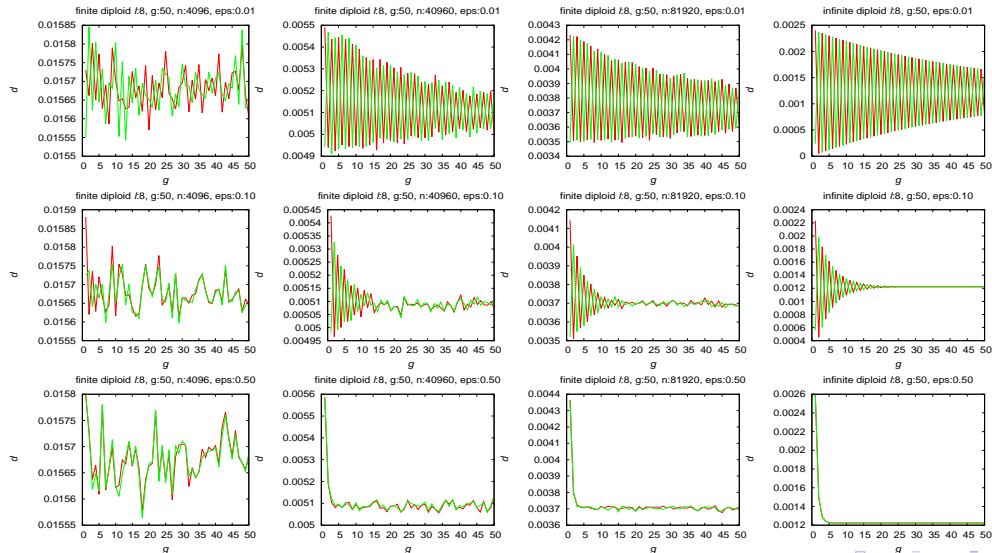
# Results: Violation in Mutation



**Figure :** Infinite and finite haploid population behavior for  $\mu$  violation and  $\ell = 12$

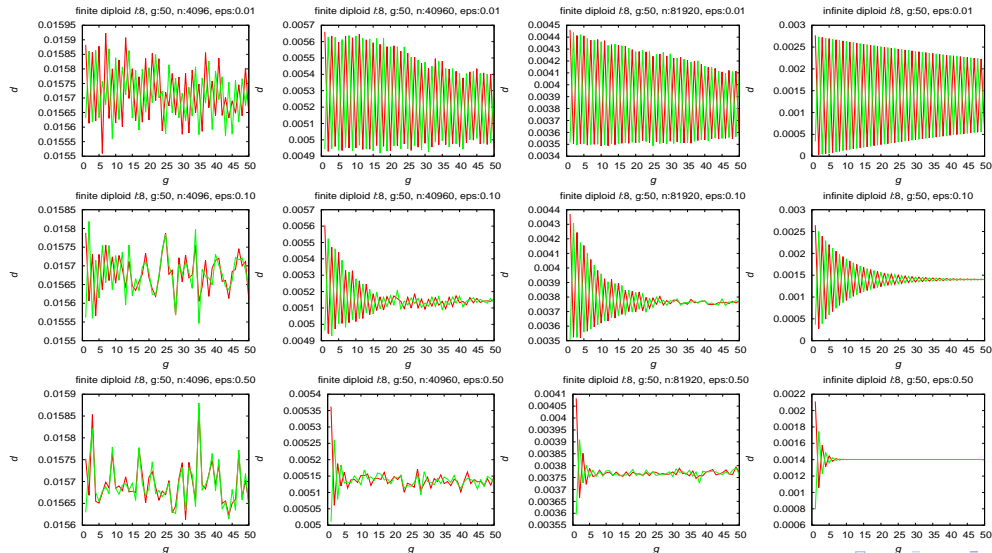


# Results: Violation in Mutation



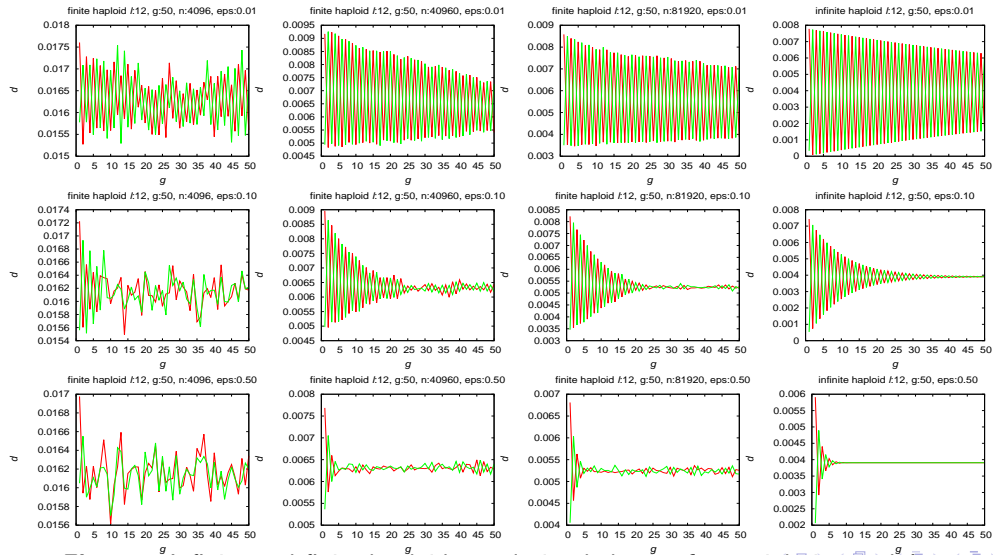
**Figure :** Infinite and finite diploid population behavior for  $\mu$  violation and  $\ell = 8$

# Results: Violation in Crossover



**Figure :** Infinite and finite diploid population behavior for  $\chi$  violation and  $\ell = 8$

# Results: Violation in Crossover



**Figure :** Infinite and finite haploid population behavior for  $\chi$  violation and  $\ell = 12$