Simulated Evolution with Noise-Driven Adaptation

Güney Erin Tekin (Exchange Student)

gtekin@student.ethz.ch

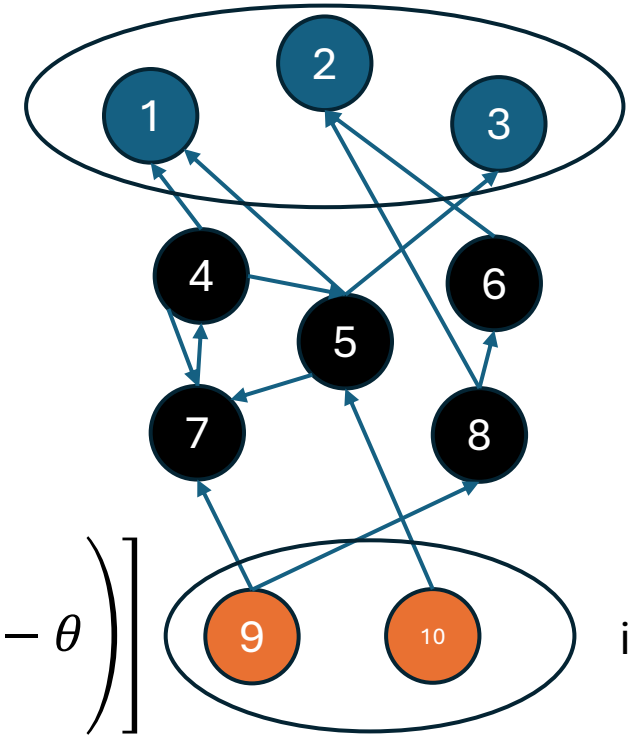
29.02.2025

Outline

- The Model for Noise-Driven Adaptation
- Selection and Mutation
- Results
  - Noise Driven Adaptation Accelerates Evolution
  - Evolution with Noise causes lower density regulatory matrices.
  - Regulatory Matrices evolved with noise are sensitive to noise level.
- Discussion

The Model

Model



$$\frac{dx_i}{dt} = v(f_i(x) - x) + \eta$$

$$f_i(x) = tanh\left[\beta\left(\sum_{j=N_t+1}^{N} G_{ij}x_j + H(i - N_t)\sum_{j=N+1}^{N+N_{in}} G_{ij}input_j - \theta\right)\right]$$

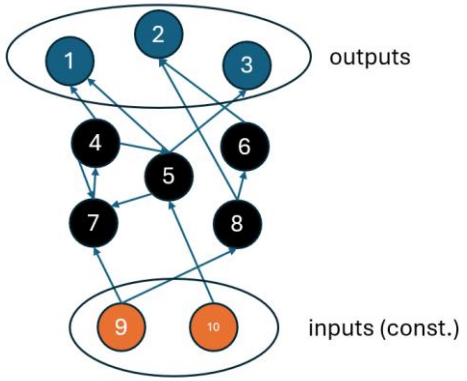
$$v(x) = v_{max}\exp\left(-\gamma\sum_{i=1}^{N_t}\left(\frac{x_i - t_i}{2}\right)^2\right) + \epsilon$$

N_t: $Number\ of\ Targets$
N_i: $Number\ of\ Inputs$

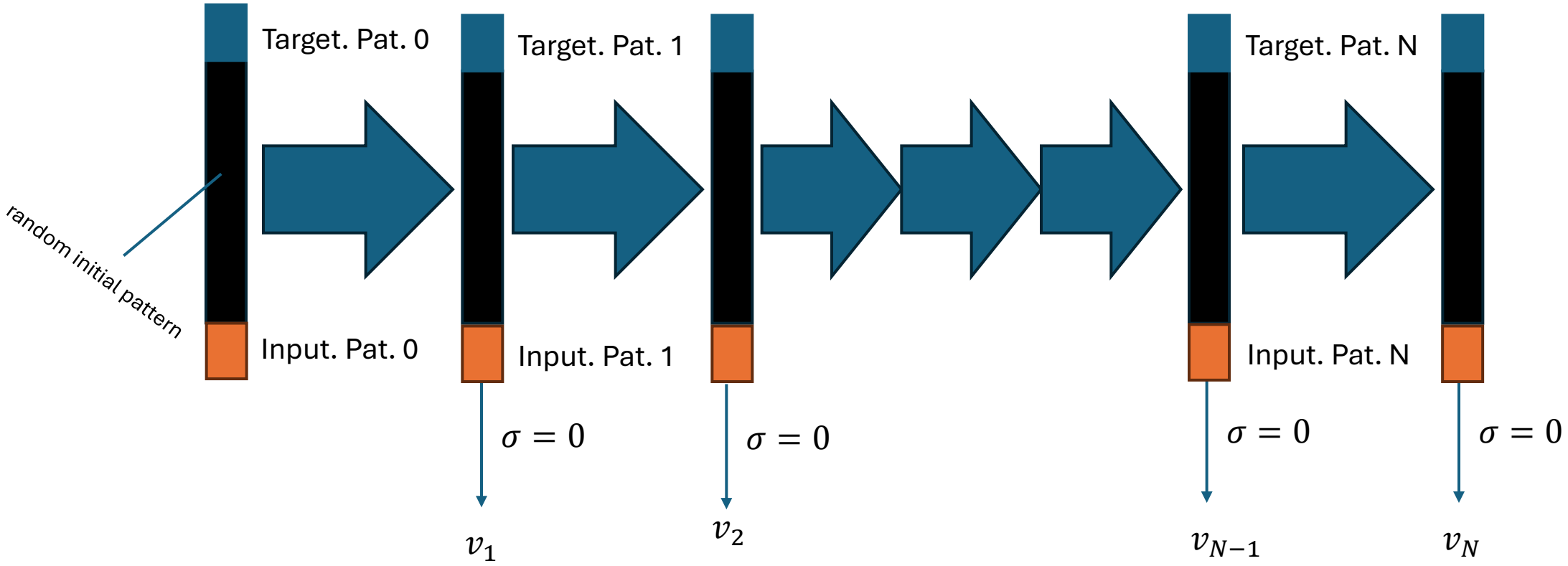
$\beta, \gamma, \epsilon, \theta$: $Parameters$
η: $Random\ Variable$

Based on a previous model by Takuya Sato, based on the previous model by Prof. Furusawa.

Periodically Changing Environment



Single Generation

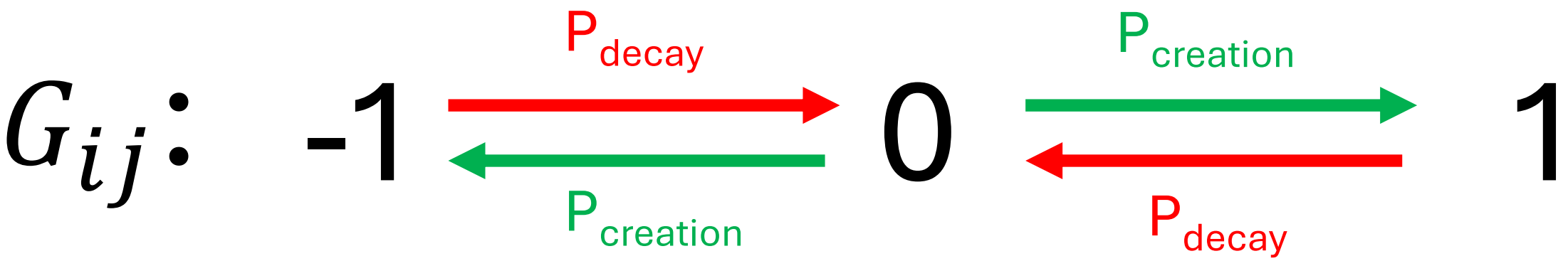


Selection

- A simple evolution model:
  - The strain with best fitness score creates offspring with mutations
  - Remaining strains are removed from the simulation
  - Fitness score defined by $mean(v_1, v_2, \dots, v_N)$

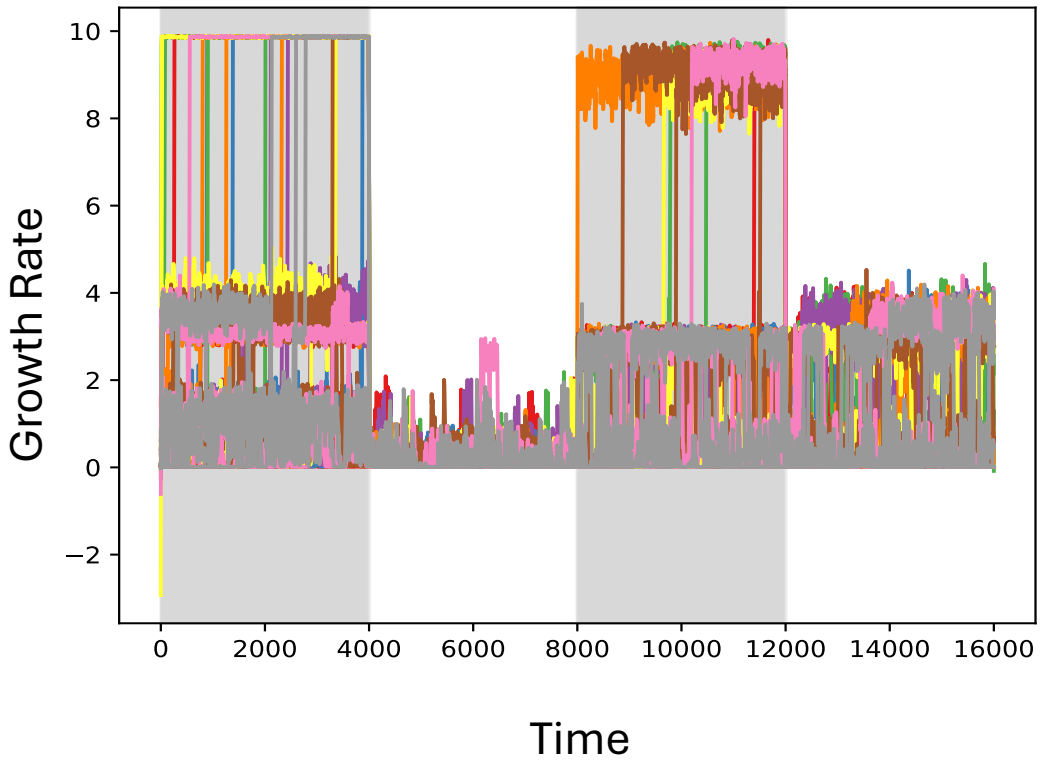
Mutation

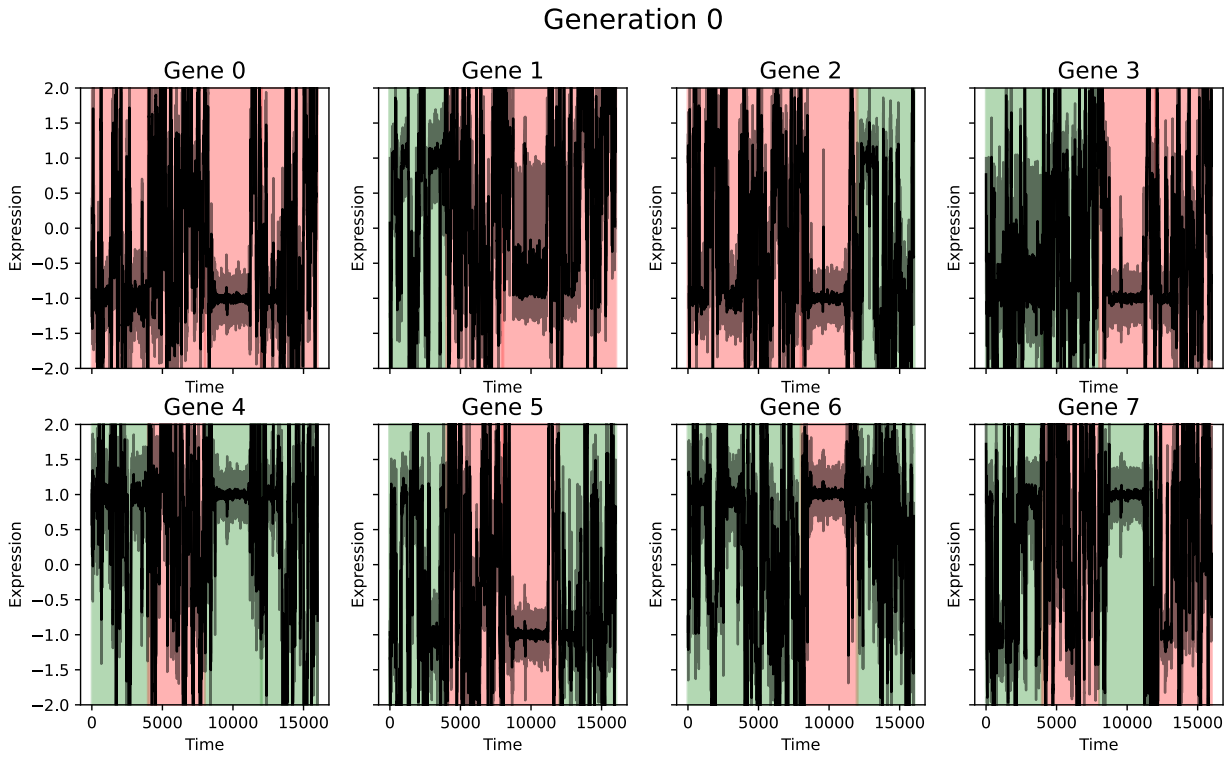
- During mutation, each pathway has a probability to decay or be created.
- The pathways that are constrained by the model are kept the same.



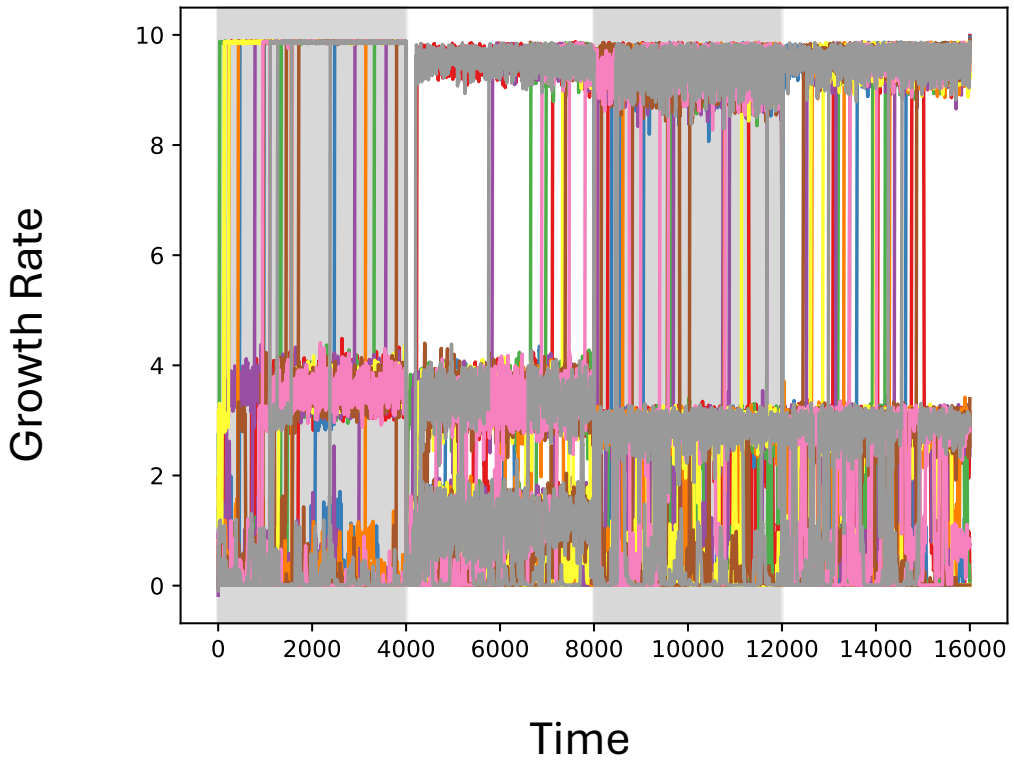
Results

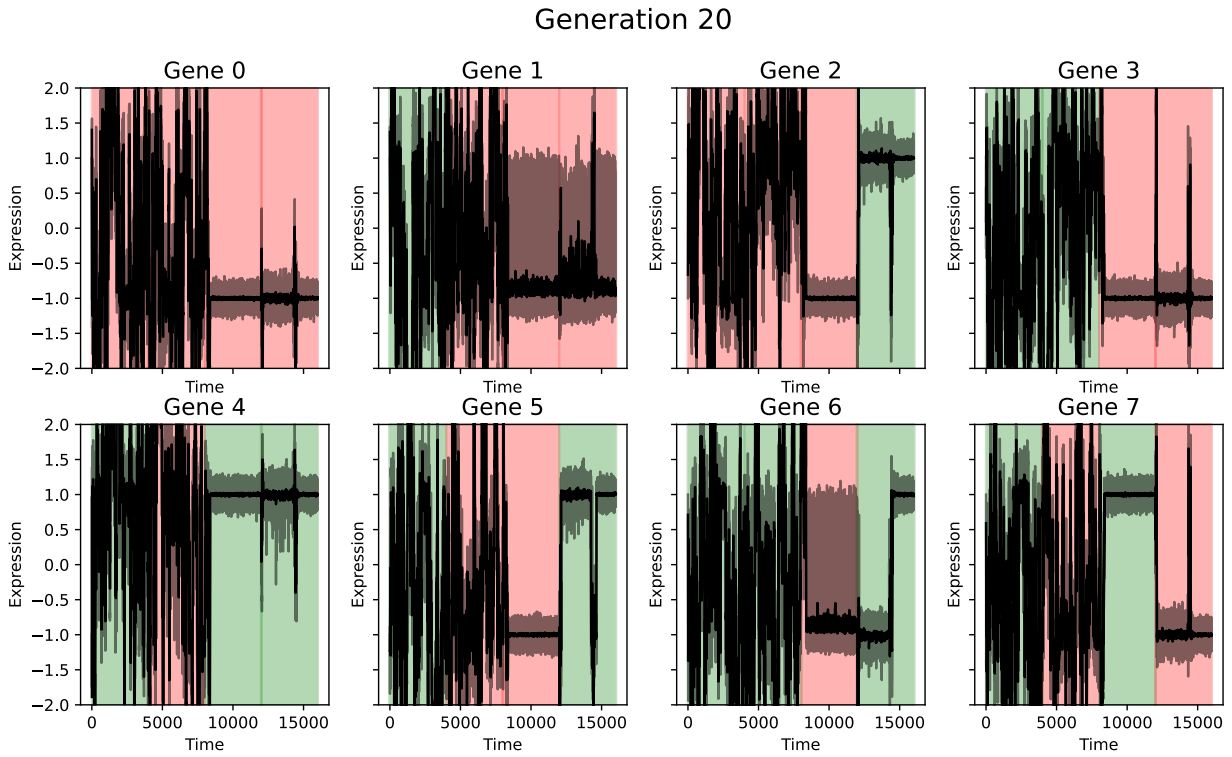
An Example for Evolution (Generation 0)



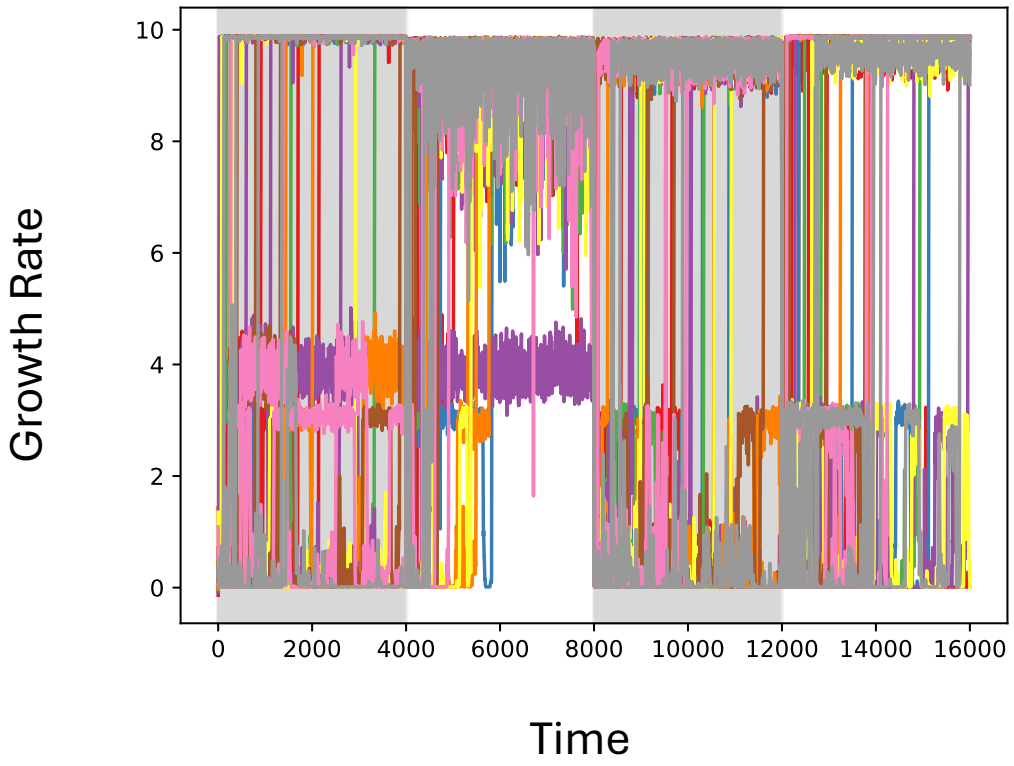


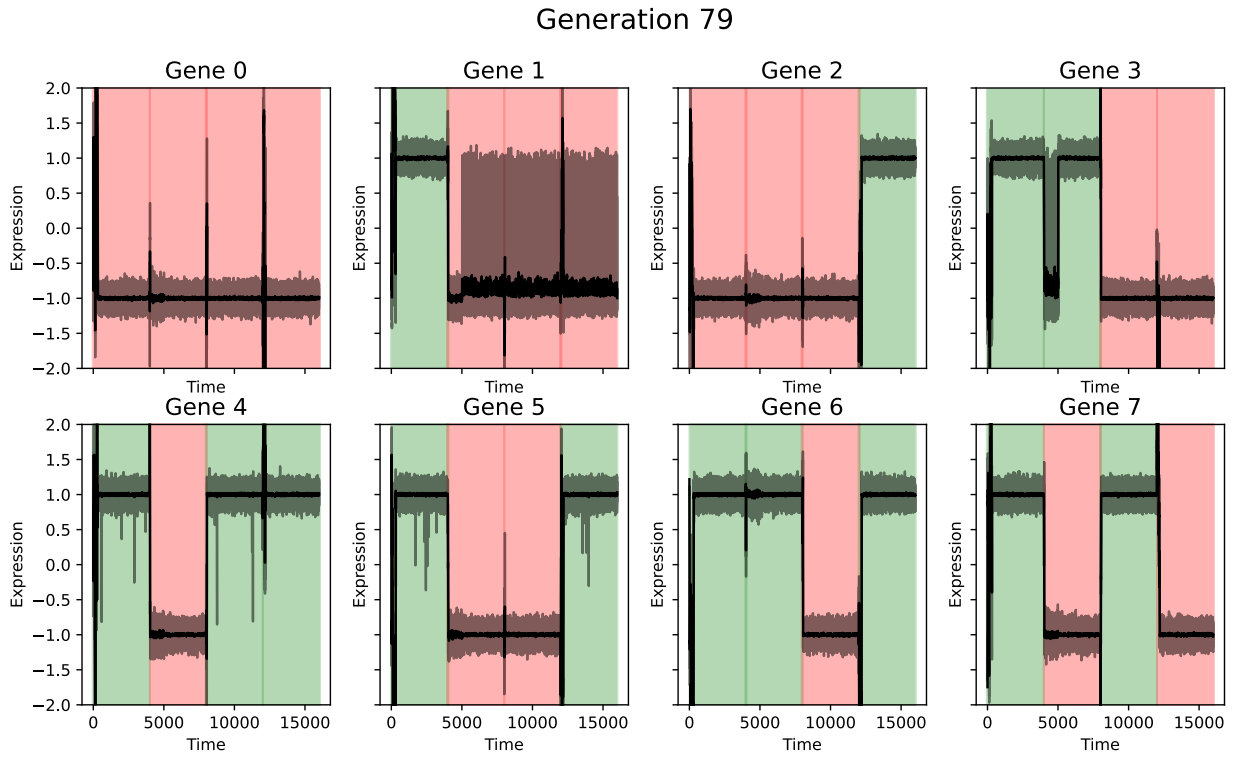
An Example for Evolution(Generation 20)



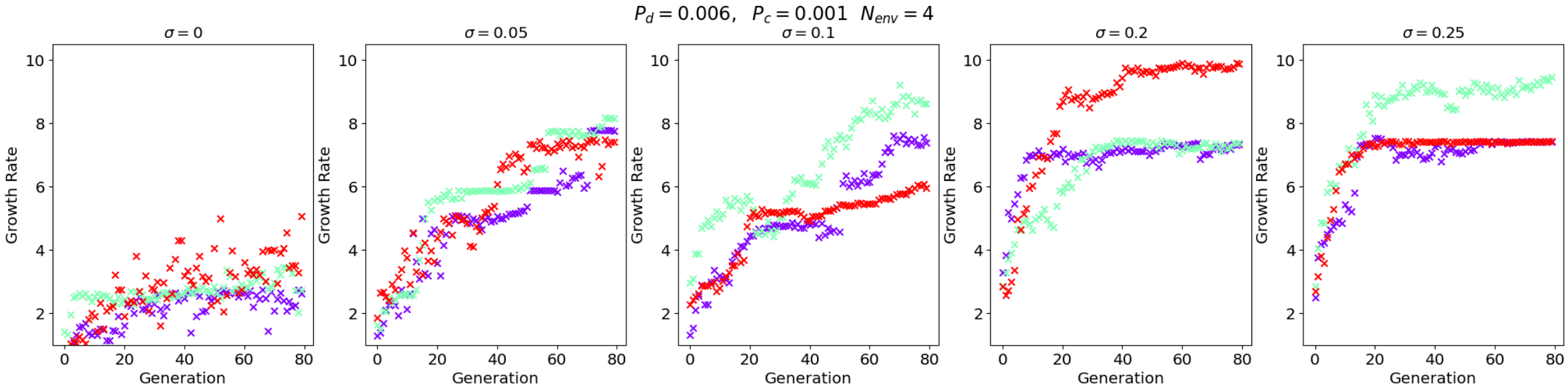


An Example for Evolution(Generation 79)



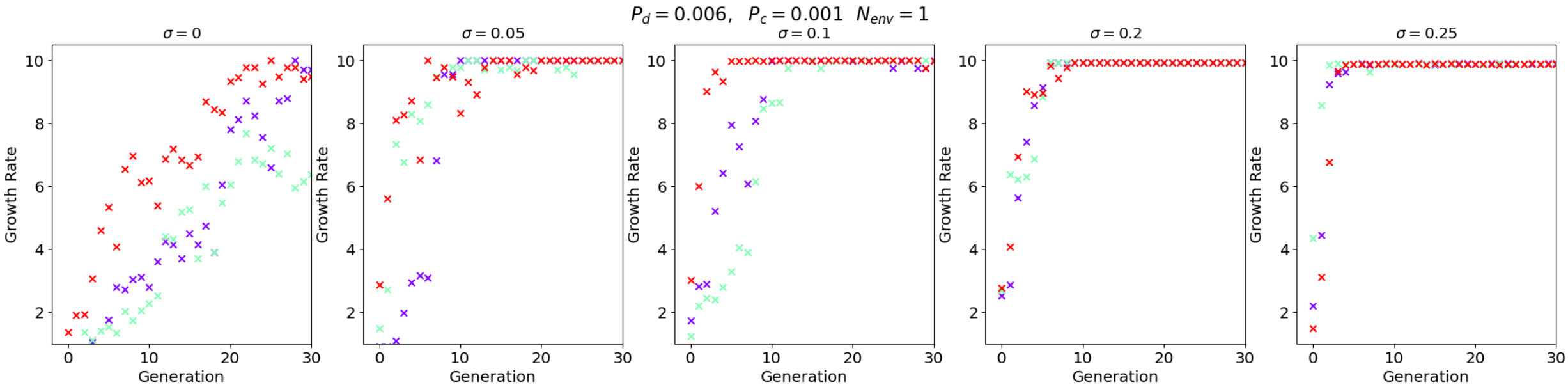


Noise is important



- When evolving with multiple environments, noise plays a crucial role:
  - Increases the evolution speed
  - Makes adaptation for multiple environments possible.

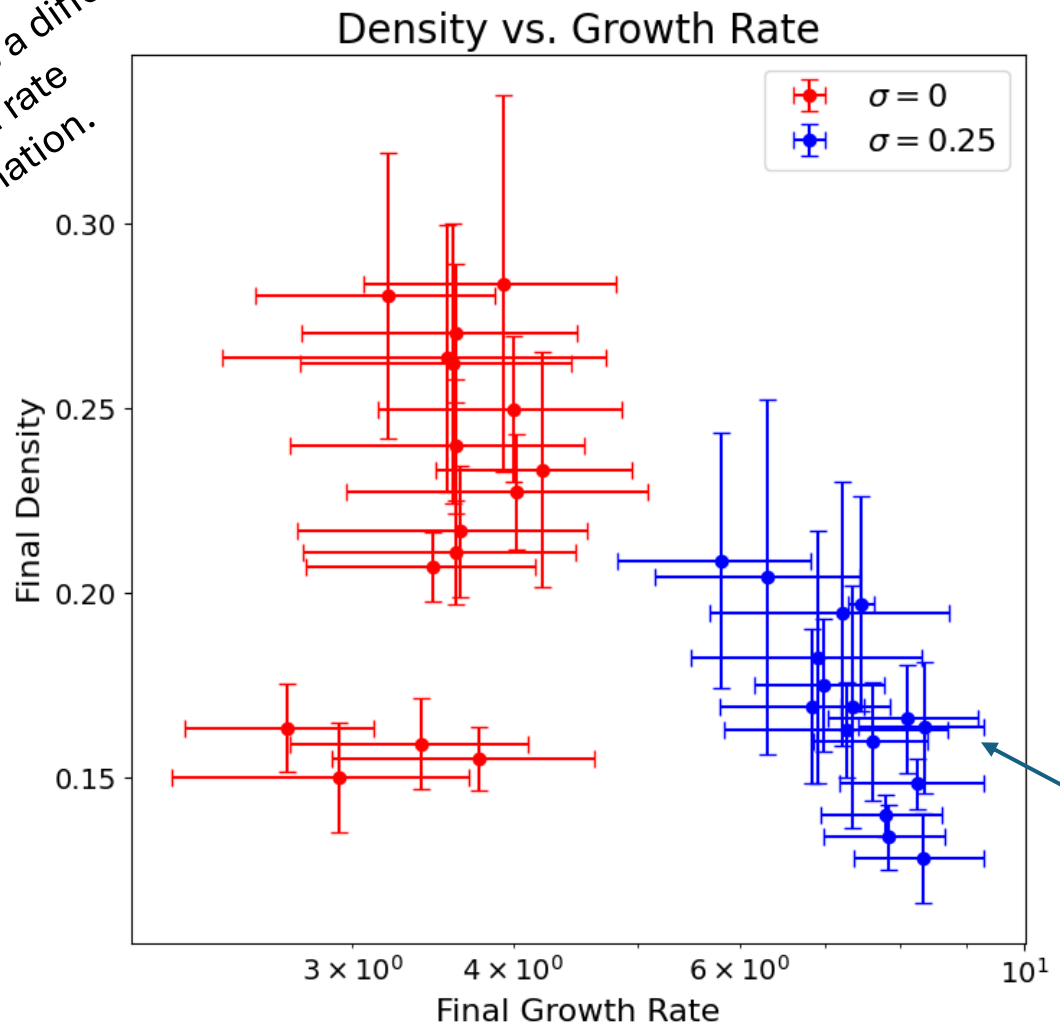
Noise is important (single environment)



- When evolving with a single environment, noise still speeds up the evolution.

Noise Driven Adaptation Causes Lower Density

Each dot is a different mutation rate combination.

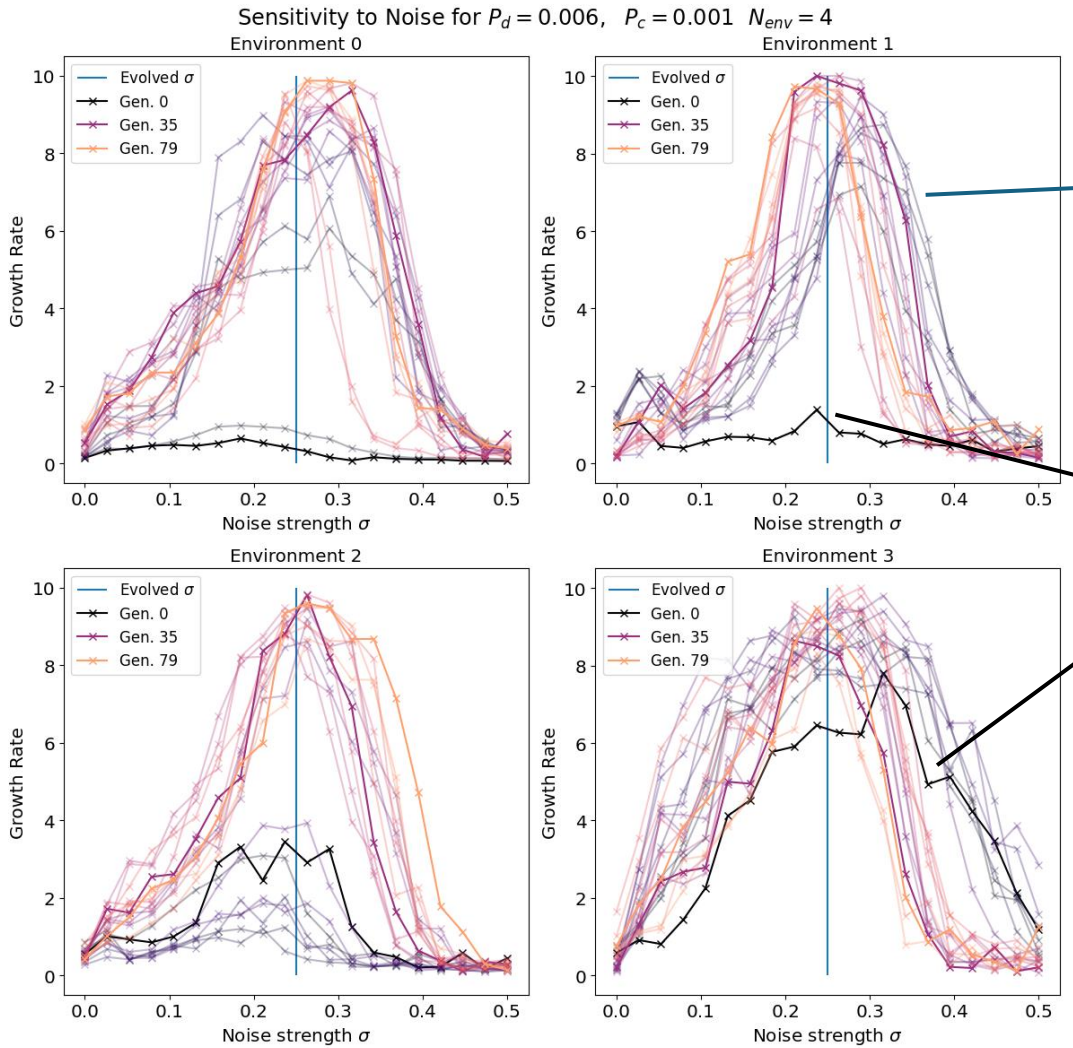


Pearson R ~ -0.76

Strains evolved with noise present have lower densities, independent of the mutation rates*.

*) The equilibrium, density of mutation is given by: $\frac{p_c}{p_c+p_d}$

Strains evolved with noise are much more sensitive to the strength of the noise.

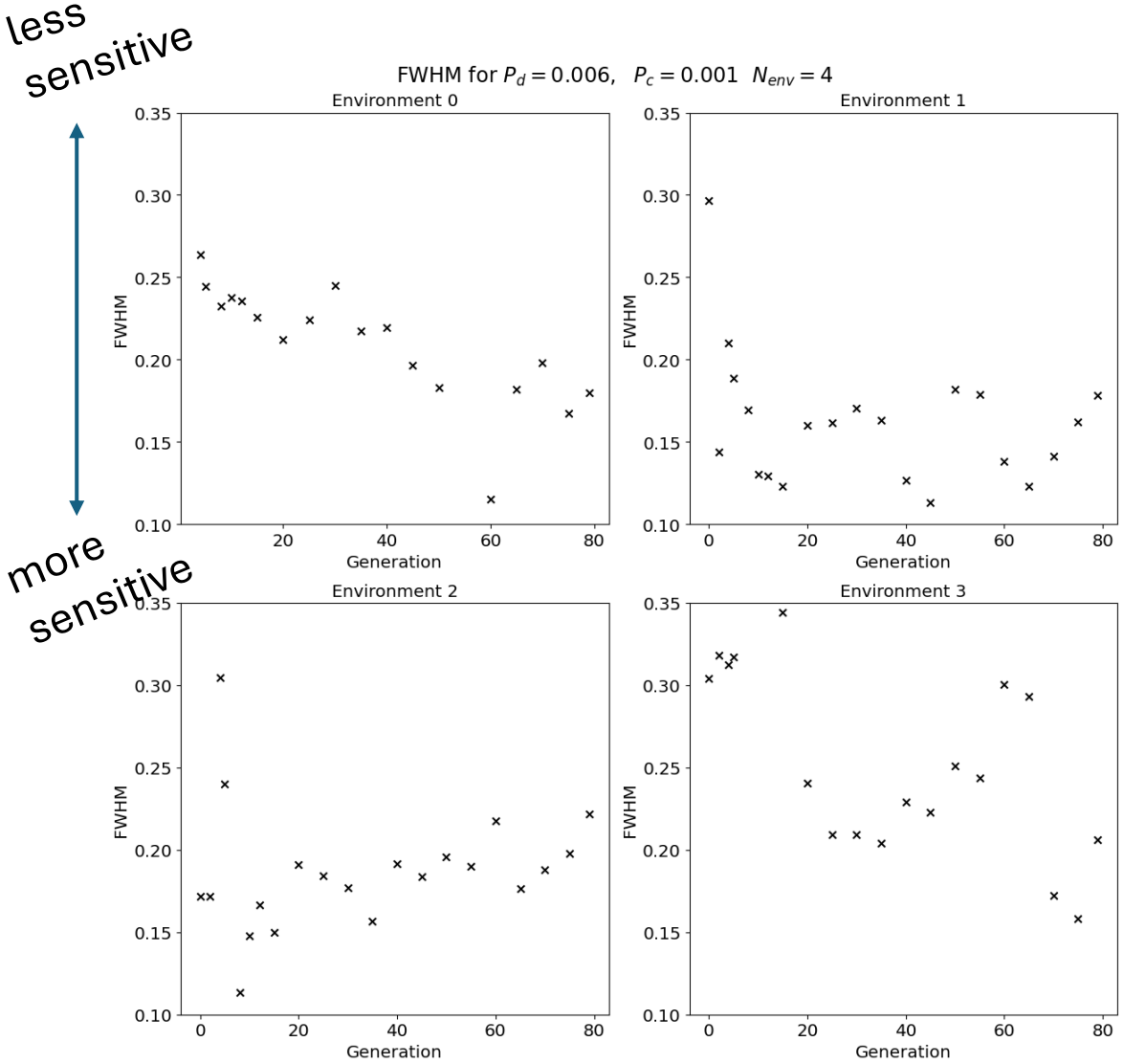


We tested the noise-driven adaptation performance for different noise strengths. Each line is different generation.

Black is the randomly generated first generation.

The growth rate has a high dependence on the noise strength. Maximal growth rate is achieved for the evolved noise strength.

Do strains get more or less sensitive to noise?

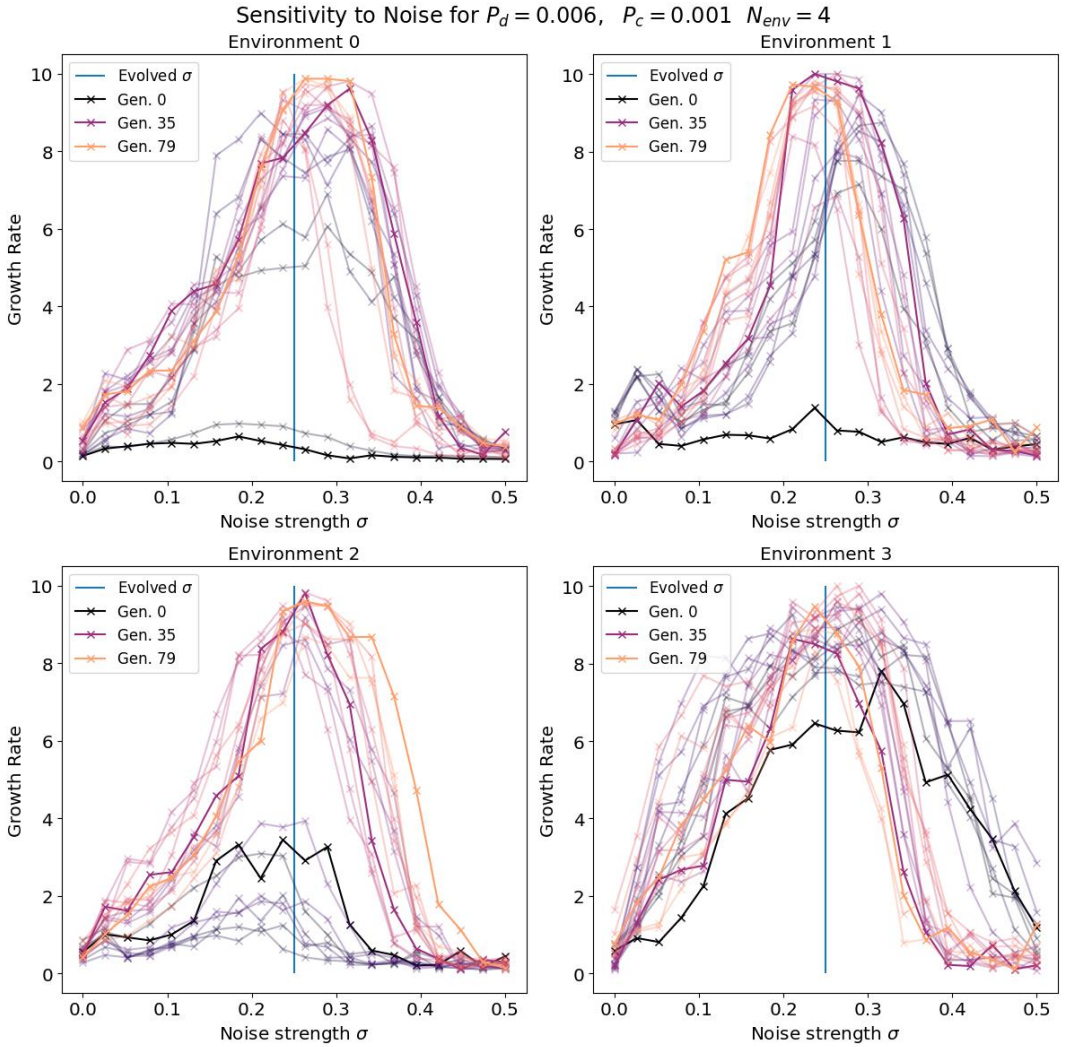


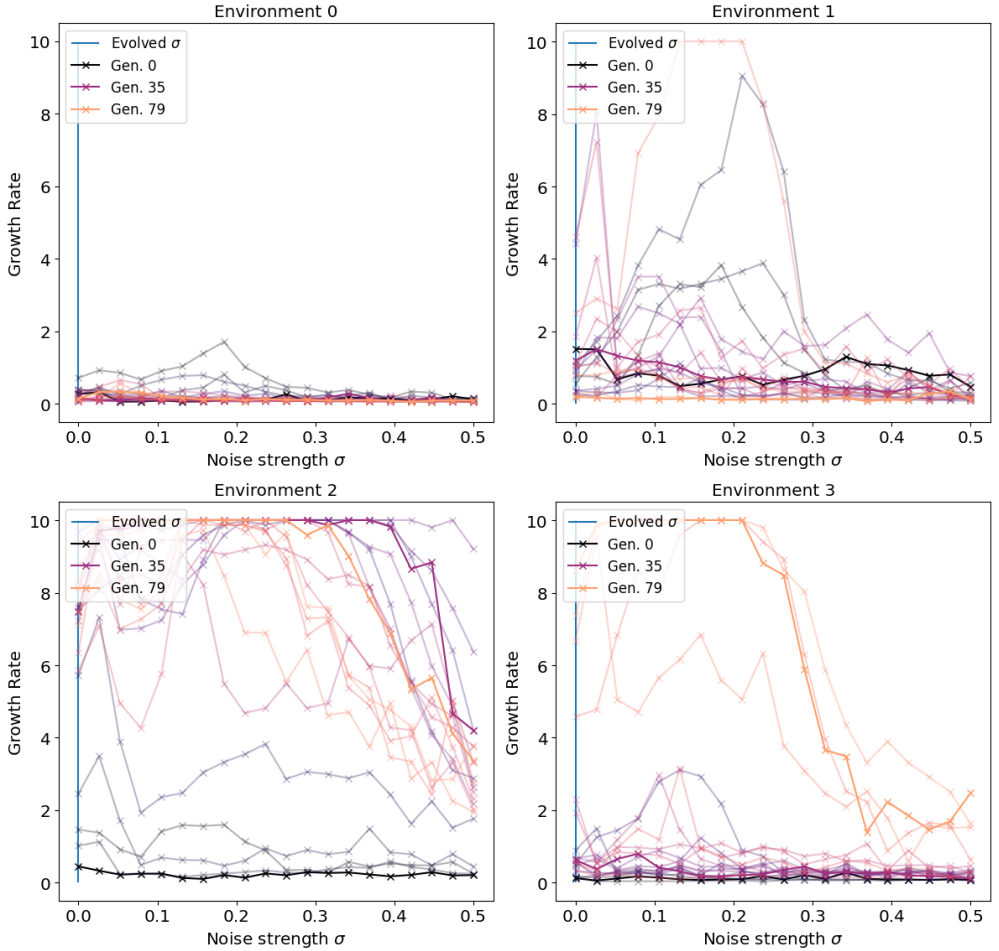
Looking at the FWHM of the curves:

- There is no clear answer, some get more sensitive, while other get less sensitive.

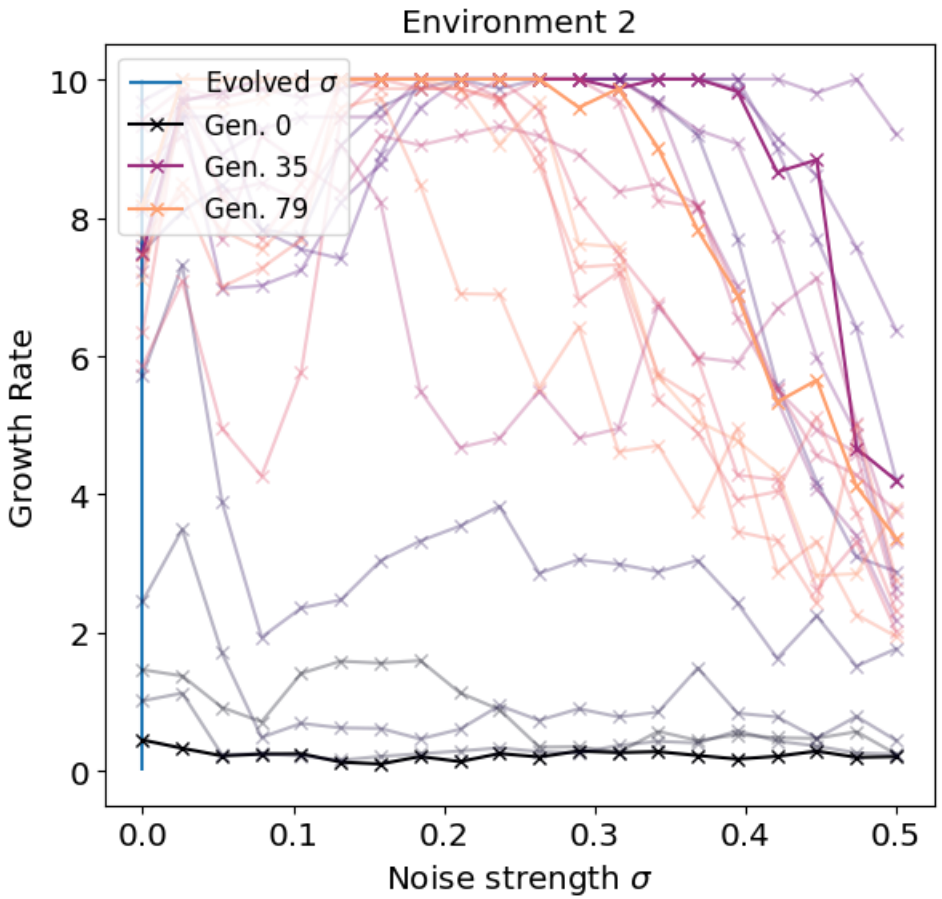
- We tested if there is correlation with the generation 0 sensitivity or growth rate. The results showed nor correlation

Strains evolved with noise are much more sensitive to the strength of the noise.





Evolution without noise causes low sensitivity



For the successfully evolved strain & environment combinations, the strain is much less sensitive to noise.

A small amount of noise is also beneficial, even if the strain evolved without any noise.

This is probably caused by noise destabilizing attractors that are not perfectly matched with the target pattern.

Summary Comparison

Evolution without Noise

- Evolution is slower/less successful.
- Resulting strains have normal regulatory matrix densities.
- If the evolution is successful for an environment, it is independent of the noise levels.

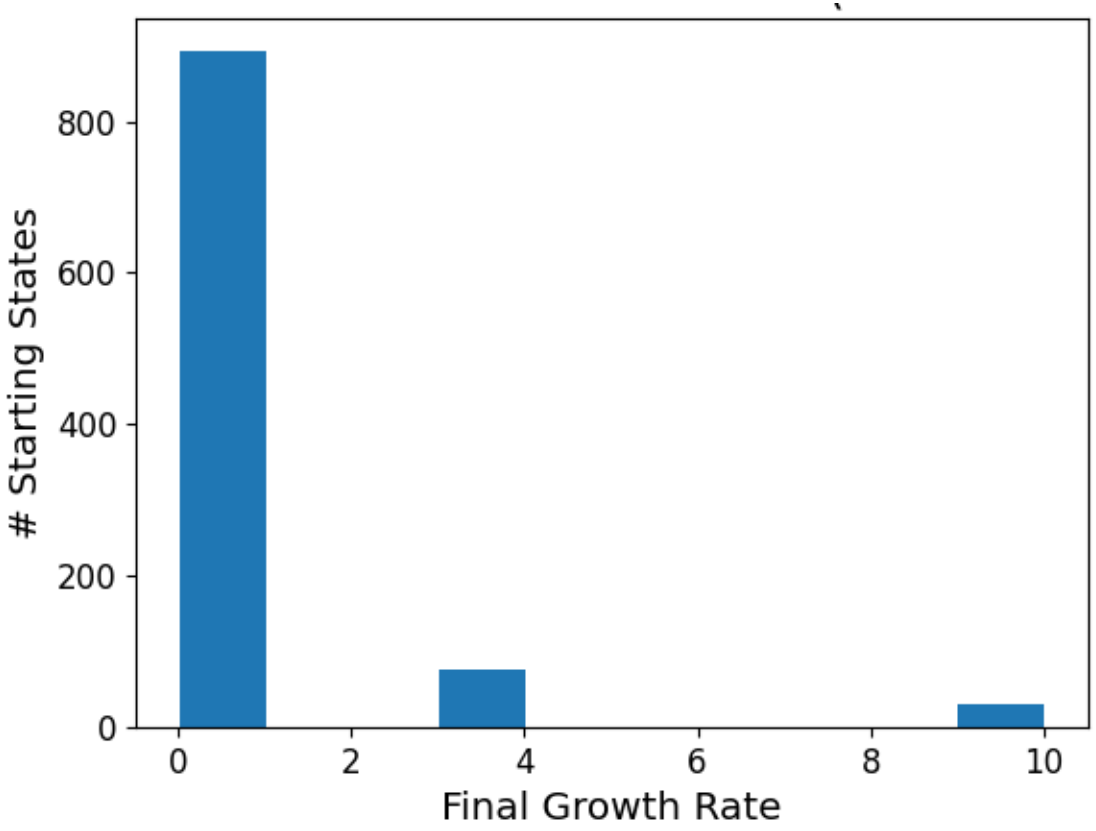
Evolution with Noise

- Evolution is faster and more successful. (Especially for multiple environments)
- The resulting strains have low regulatory matrix densities.
- The resulting strains are much more dependent on the noise level.

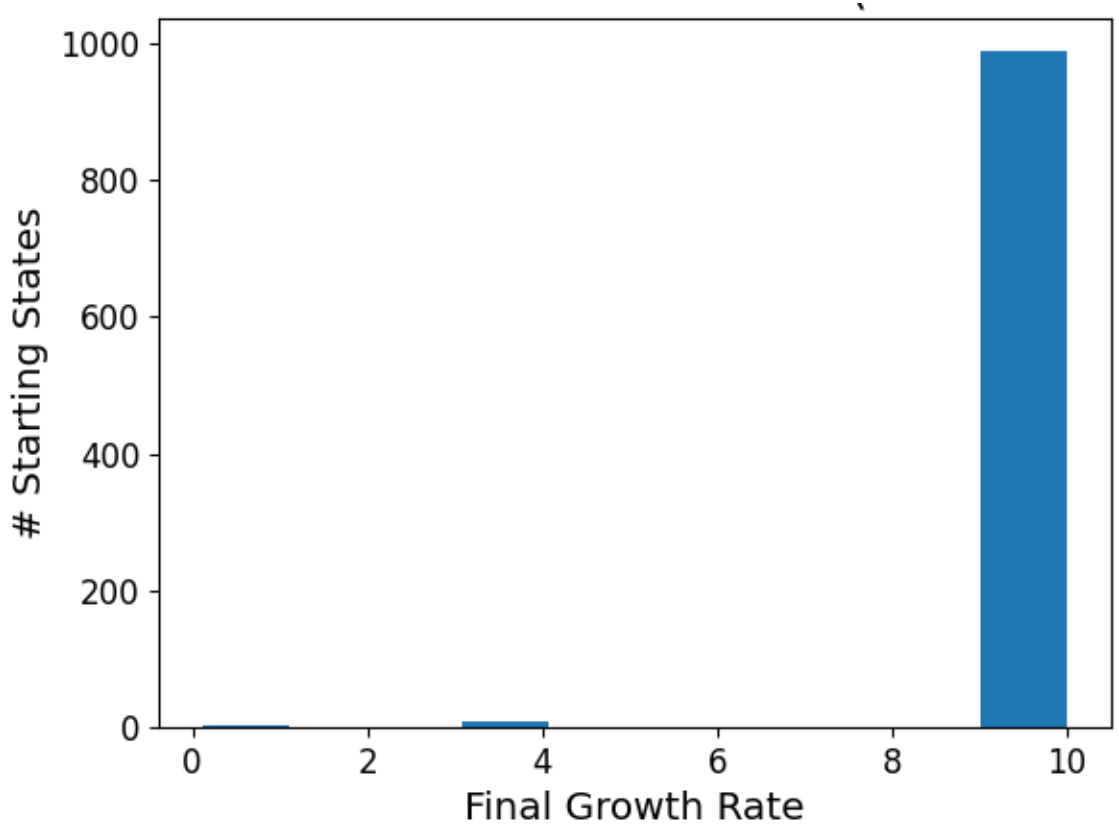
Discussion (Noise Sensitivity)

- We found that the strains evolved **without** noise-driven adaptation are more **resilient** to changes in noise level. (if they are successful)
- We hypothesize that this is explained by:
- High growth rate states in these strains have high basin fractions. This creates a resistance to noise, since most states will fall into an attractor with high growth rate.

Basins



Evolved **with** Noise



Evolved **without** Noise

Discussion (Noise Sensitivity)

- We also found that strains evolved **with** noise have **high sensitivity** to noise levels.
- This is very intuitive. The success of these strains depends on noise driven adaptation, more than their basins of attractions.
- Thus, they have no mechanisms to compensate for changes in noise levels.

Discussion (Density)

- Current results show that: for noise driven adaptation, lower densities are beneficial.
- A possible (untested) explanation might be:
  - At higher densities for each gene, more genes will have a regulatory connection to the gene.
  - This will act as an averaging over the independent noise terms.
  - Since the noise term has mean 0, the effective amplitude of the noise term is decreased with increasing density.

Discussion (Limits of the Model)

- In the current version of the model, the threshold θ and the noise strength σ are kept constant.
- Allowing these to mutate might improve the evolutionary speed in both cases.

- Also, during selection step of the model, we only considered the best performing strain for the next generation. Considering multiple strains might be beneficial.

Further Ideas

- Test different fitness scores and selection strategies.
- Implement mutation with constant density to investigate the connection with density
- Do similar testing to “Evolution of Robustness to Noise and Mutation in Gene Expression Dynamics”, K. Kaneko (2007) to investigate the noise sensitivity.

Questions

Thanks for Listening.

Software

- All of the code is written in Python using Numba and NumPy for acceleration.
- The code is easily extendable, with templates for implementing new fitness cores and selection criteria.
- It is available on ….

Final Densities for Best Mutation Rates