Evolutionary Identification of Wind Turbine Dynamics

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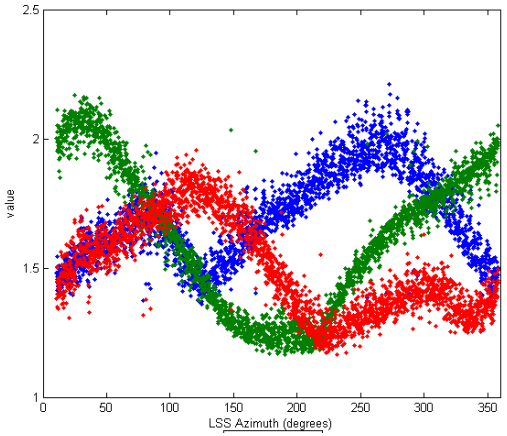
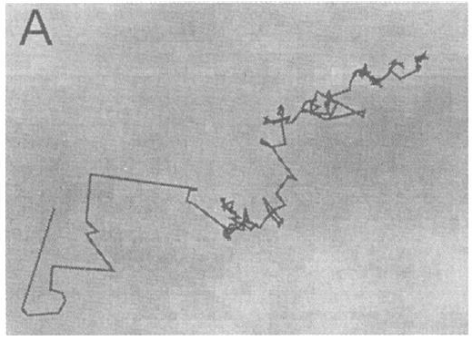
System Identification



$$y = f(t, x, a, b, c)$$



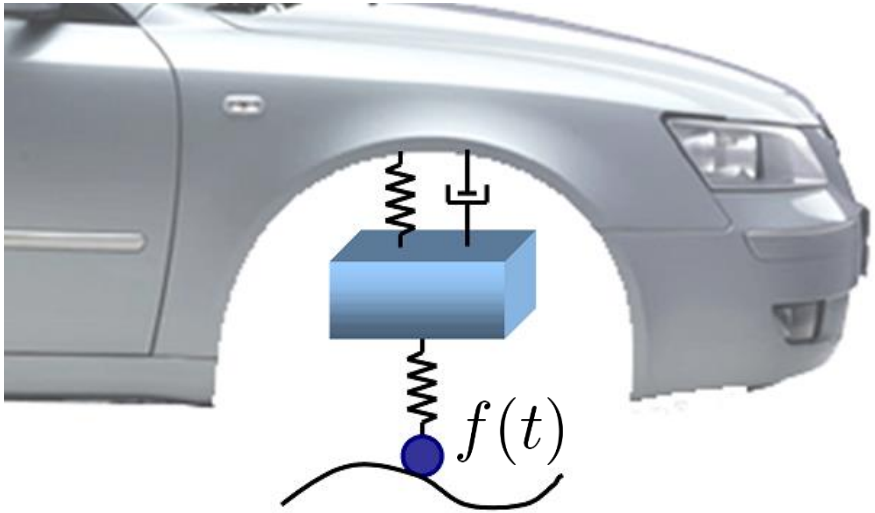
$$y = f(t, x, a, b, c)$$

System Identification

First Principles

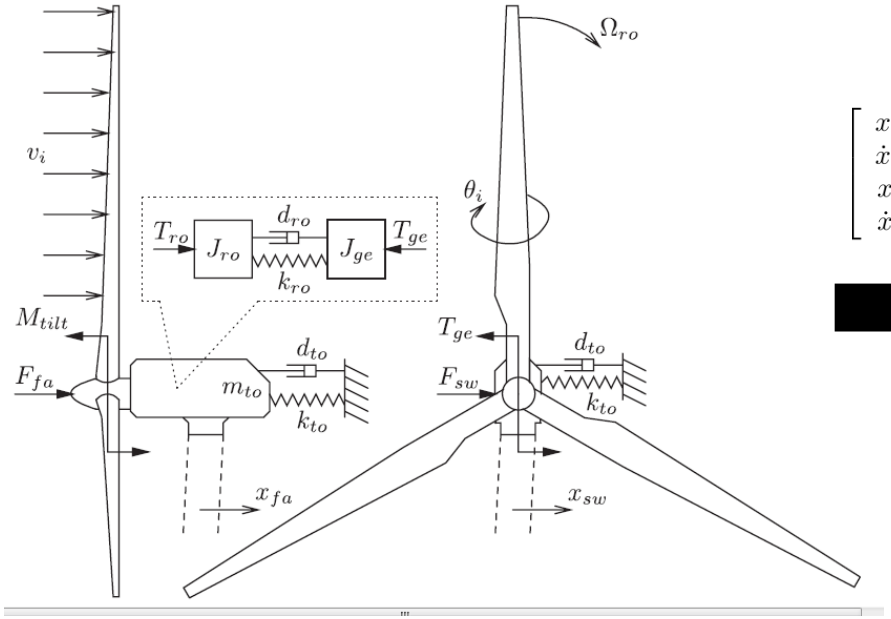
$$\sum F = m\ddot{x}$$

System Identification



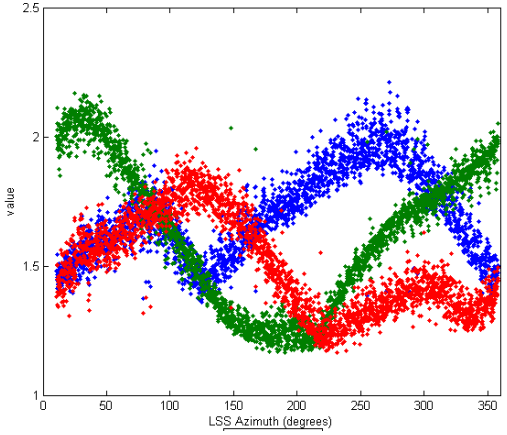
$$m\ddot{x} + c\dot{x} + kx = f(t)$$

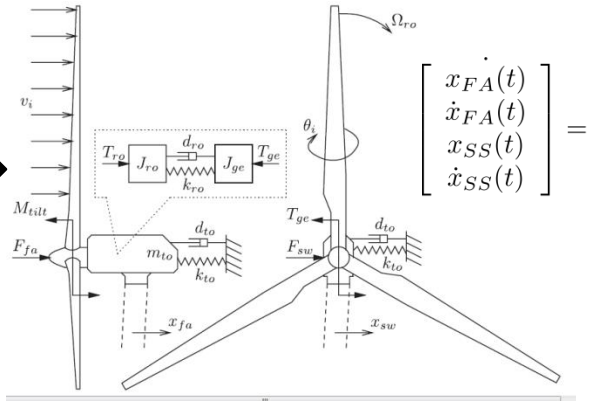
System Identification



$$\begin{bmatrix} \dot{x}_{FA}(t) \\ \dot{x}_{FA}(t) \\ \dot{x}_{SS}(t) \\ \dot{x}_{SS}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_{to}}{m_{to}} & \frac{81R}{32H^2}\frac{h_{Mz}}{m_{to}} - \frac{d_{to}}{m_{to}} - \frac{3h_{Fx}}{m_{to}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{27R}{16H^2}\frac{h_{Fz}}{m_{to}} & -\frac{k_{to}}{m_{to}} & -\frac{d_{to}}{m_{to}} \end{bmatrix} \begin{bmatrix} x_{FA}(t) \\ \dot{x}_{FA}(t) \\ x_{SS}(t) \\ \dot{x}_{SS}(t) \end{bmatrix}$$
$$+ \begin{bmatrix} 0 & 0 \\ 0 & \frac{3k_{Fx}}{m_{to}} \\ 0 & 0 \\ \frac{3}{2H}\frac{1}{m_{to}} & 0 \end{bmatrix} \begin{bmatrix} T_{gen} \\ \beta \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{3h_{fx}}{m_{to}} \\ 0 \\ \frac{3h_{fx}}{m_{to}} \end{bmatrix} V$$

System Identification





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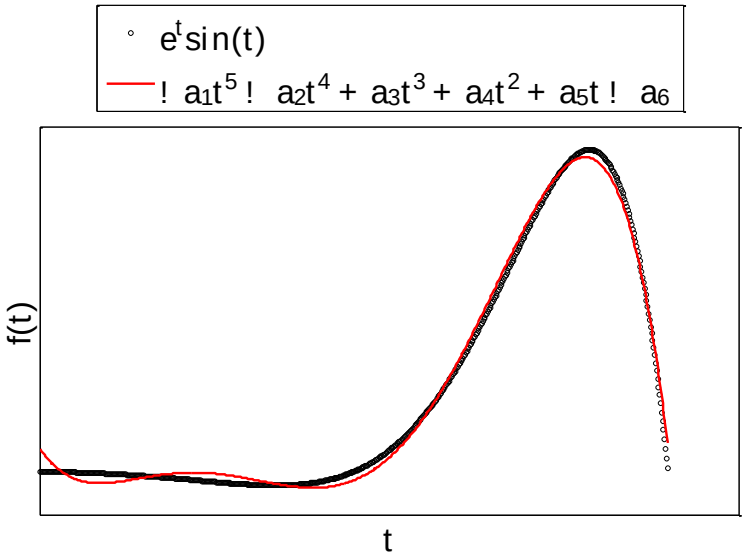
System Identification

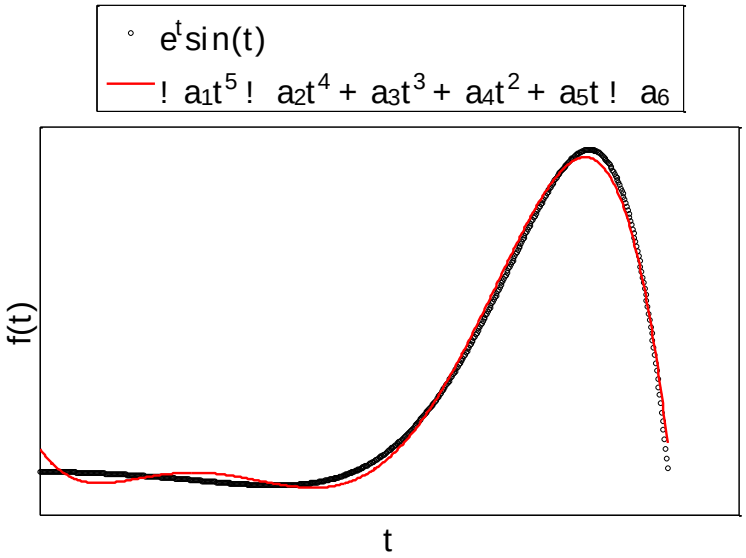


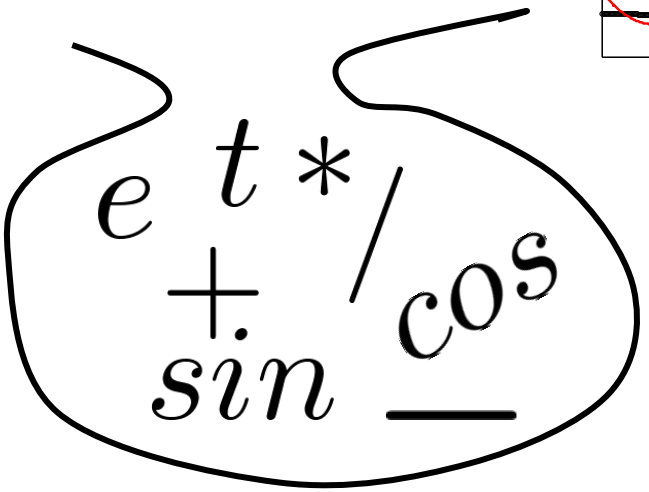
Model $-a_1 t^5 - a_2 t^4 + a_3 t^3 + a_4 t^2 + a_5 t - a_6$

$-t^5 - t^4 + t^3 + t^2 + t - 1$ $a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6$

Structure / Form Parameters

System Identification

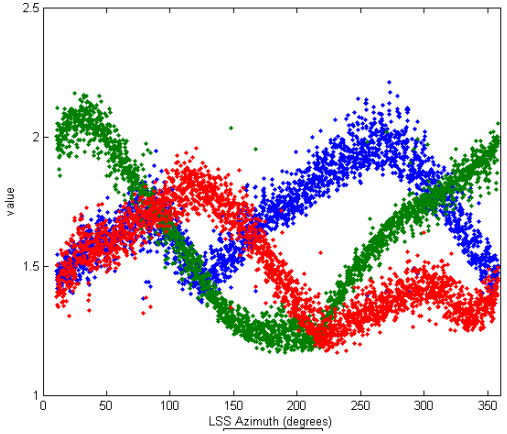


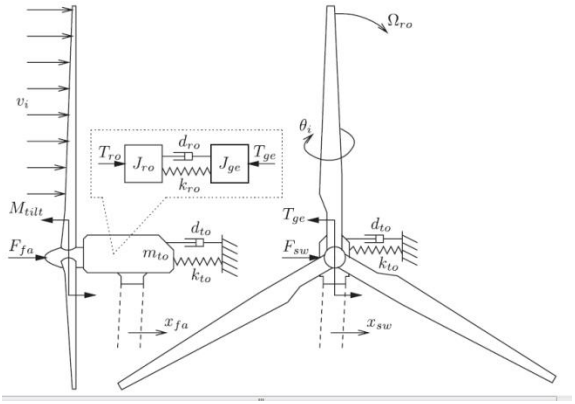


Symbolic Regression

$$e^t sin(t)$$

Symbolic Regression



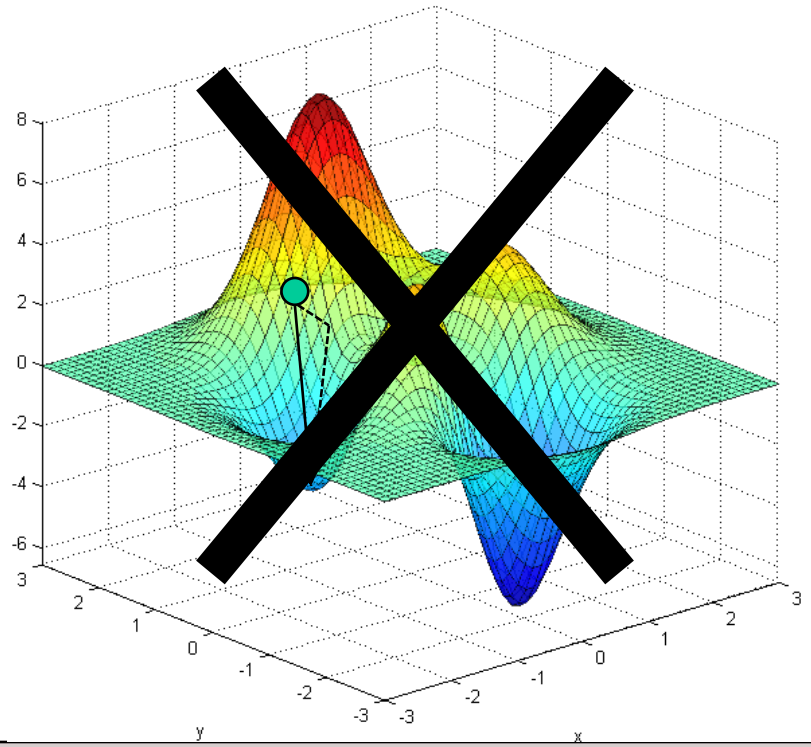


$$y = f(t, x, a, b, c)$$

Symbolic Regression

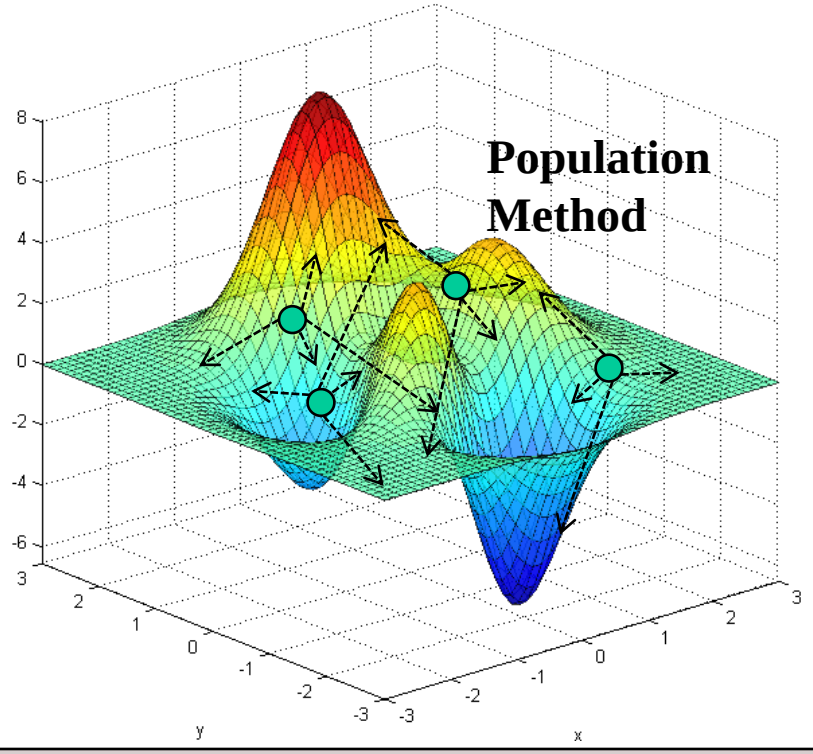
Gradient method

$$\vec{x} = \vec{x} + \alpha \nabla f(\vec{x})$$



Stochastic Method

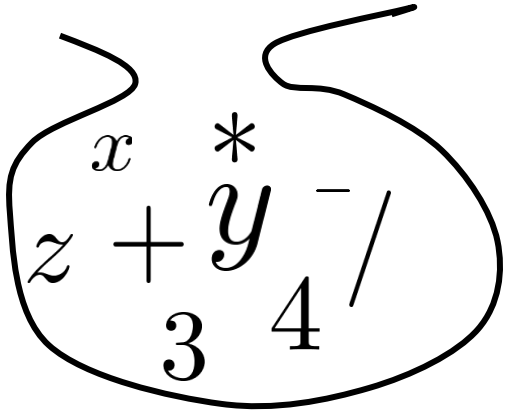
$$\vec{x} = tweak(\vec{x})$$



Genetic Programming

Initial Population

$f_1 = x * y + z$
$f_2 = x/3 + y/z$
$f_3 = y - \frac{4}{(z+3)} + x$
$f_4 = y - z$
$f_5 = 3 * (x - y) + z^2$



Fitness

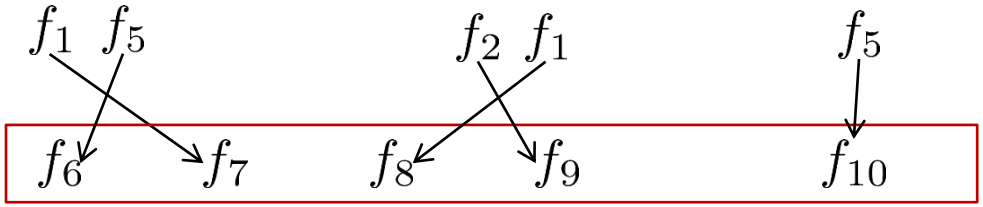
$E_i = \sum_{n=1}^{N} |f(n)^* - f_i(n)|$

Solution

Selection

$f_1 = x * y + z$
$f_2 = x/3 + y/z$
$f_3 = y - \frac{4}{(z+3)} + x$
$f_4 = y - z$
$f_5 = 3 * (x - y) + z^2$

Breeding

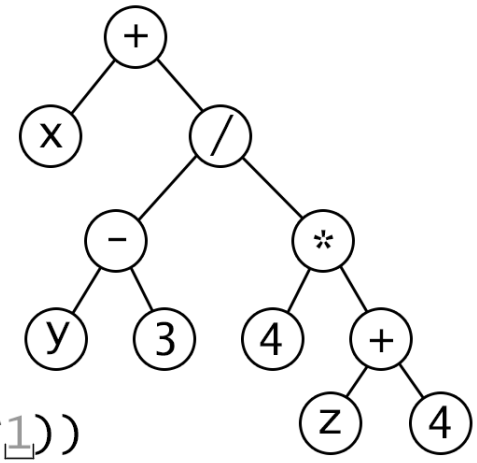


Genetic Programming - Representation

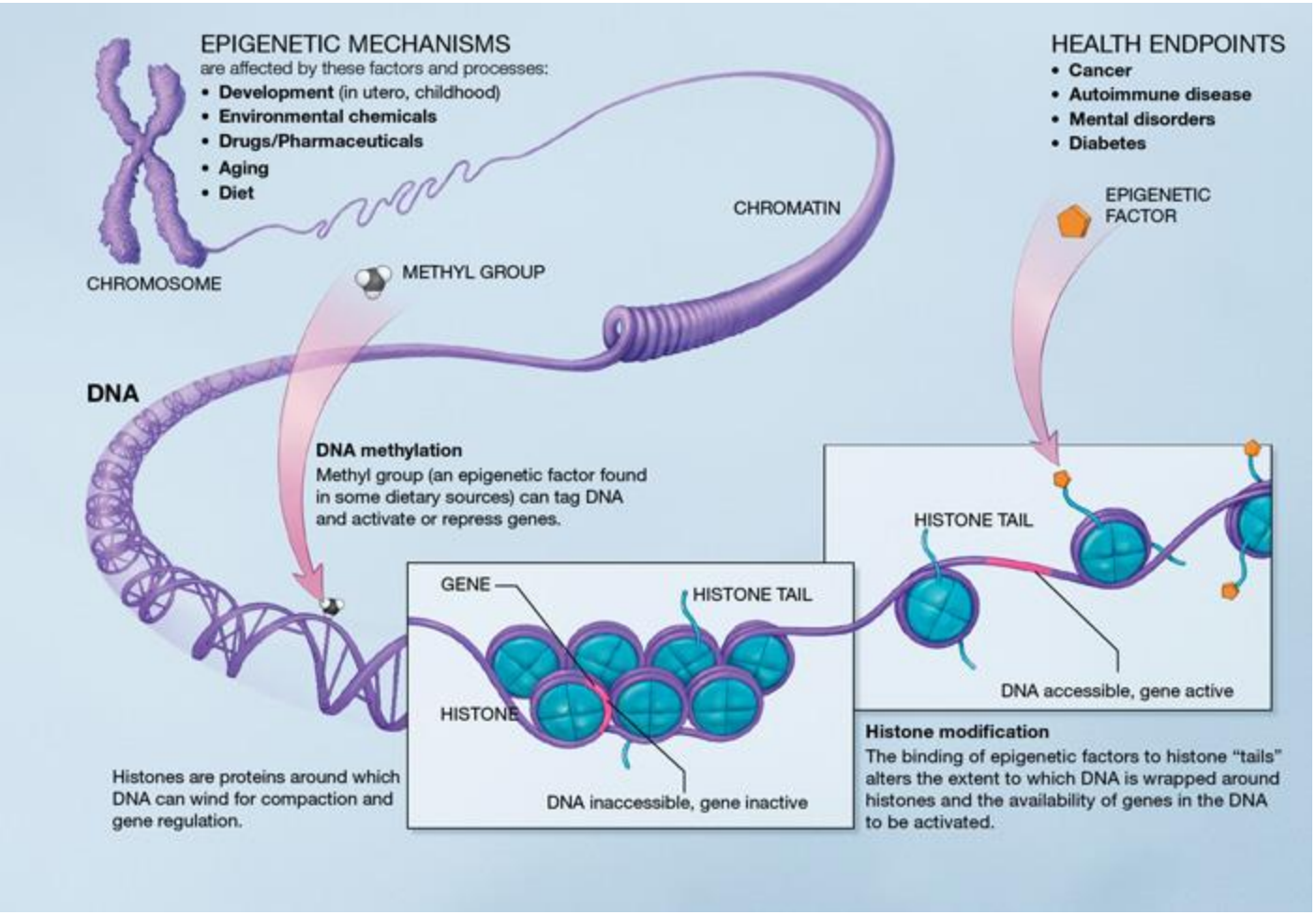
- Developmental
- Linear

Genotype	
insert(x)	x
add	(x+0)
insert(y)	(x+y)
subR	(x+(y-0))
insert(3)	(x+(y-3))
UP	(x+(y-3))
divR	(x+(y-3)/1)
insert(4)	(x+(y-3)/4)
mul	(x+(y-3)/(4*1))
insert(z)	(x+(y-3)/(4z))
add	(x+(y-3)/(4(z+0))
insert(4)	(x+(y-3)/(4(z+4))

Phenotype



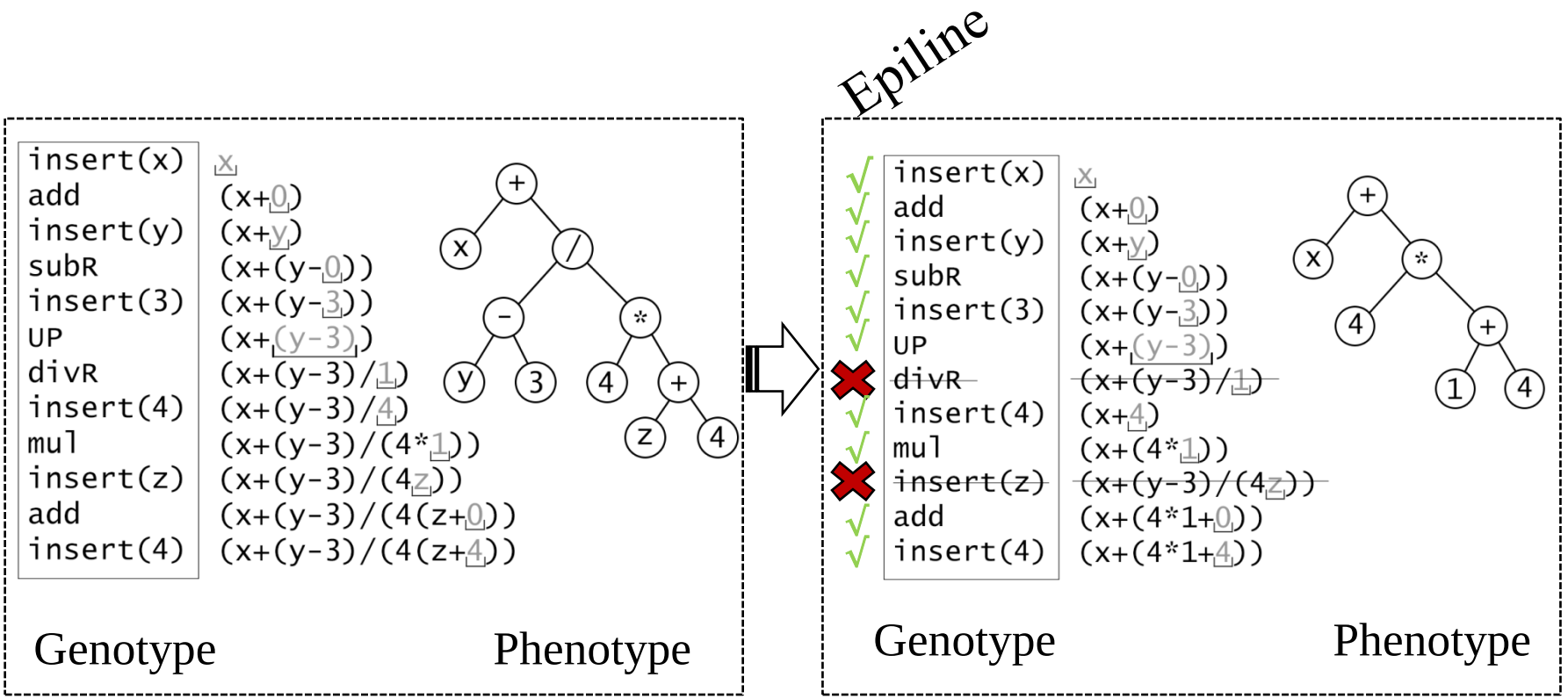
Epigenesis



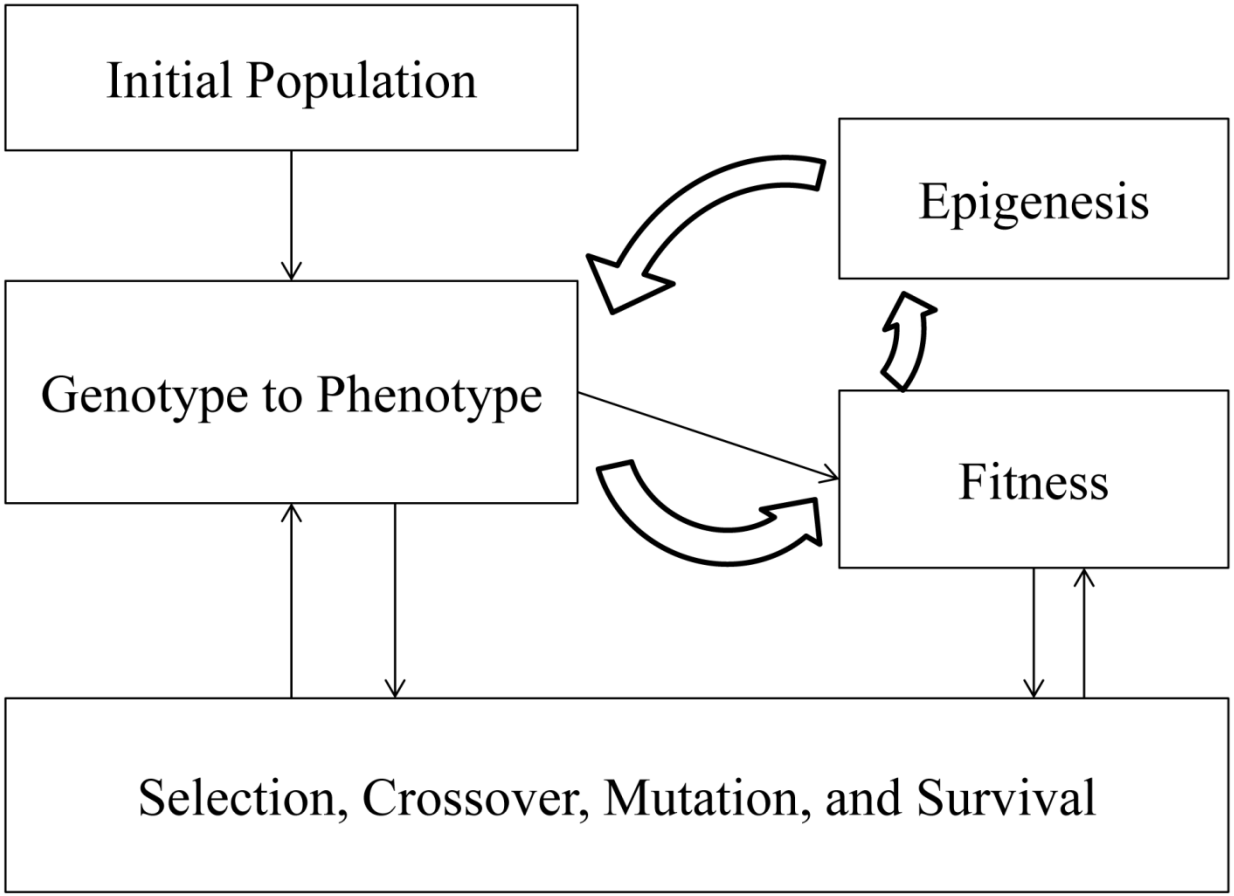
Environment

Inheritance

Genetic Programming - Epigenesis



Genetic Programming - Epigenesis



Genetic Programming - Epigenetic Hill Climber

```
gen ⟵ genotype of individual
epi ⟵ epigenetic line of individual
phen ⟵ phenotype equation of individual
L ⟵ length of genotype
sr ⟵ switching rate
for number of hill climbing iterations do
    epiTemp ⟵ epi
    for i ∈ L do
        if rand() < sr then
            /* flip the on/off state of marked
               indices in the epiline          */
            epiTemp(i) ⟵ !epi(i)
        end
    end
    /* get equation from genotype with updated
       gene expression                         */
    phenTemp ⟵ GenToPhen(gen,epiTemp)
                              /* update equation */
    if fitness(phenTemp) < fitness(phen) then
        epi ⟵ epiTemp
        phen ⟵ phenTemp
                           /* secondary size metric */
    else if fitness(phenTemp) == fitness(phen) and
    size(phenTemp) < size(phen) then
        epi ⟵ epiTemp
        phen ⟵ phenTemp
    else
    end
end
```

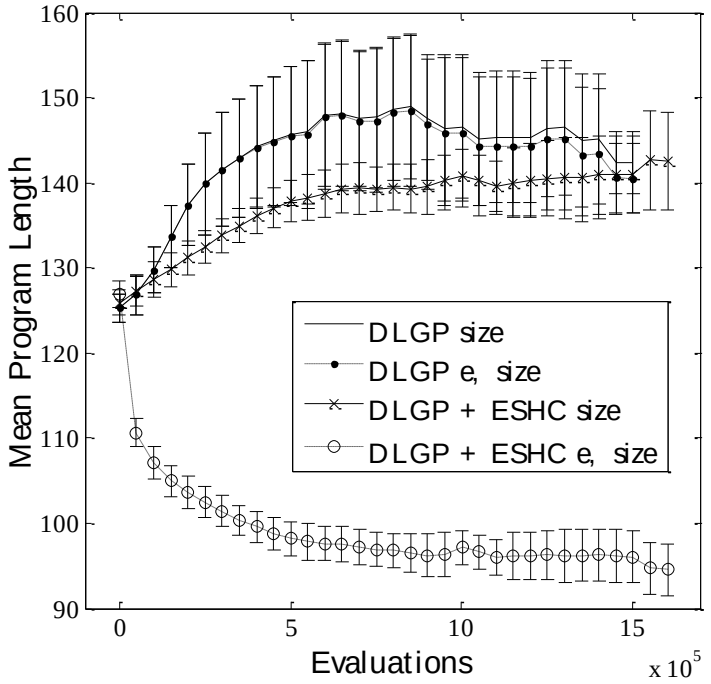
Algorithm 1: ESHC for one individual in population.

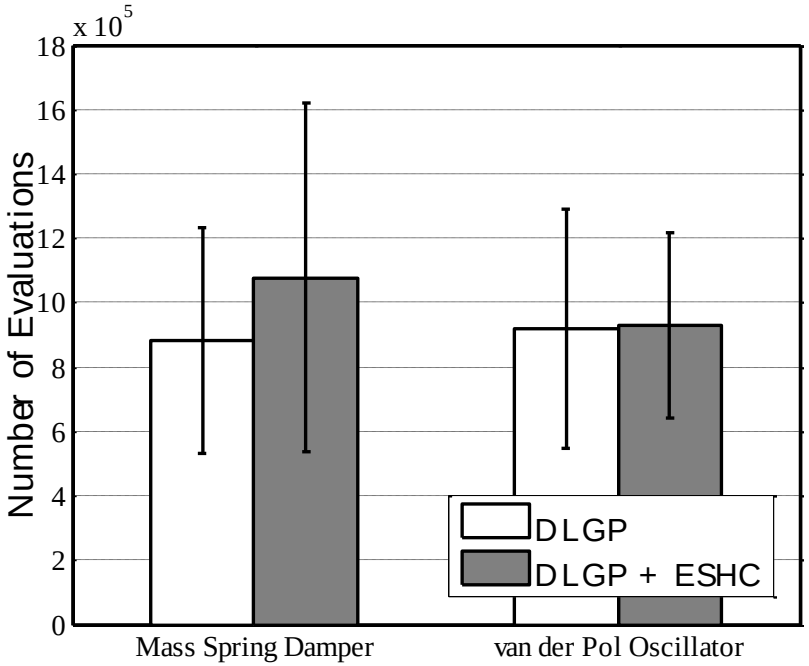
1. Randomly switch some genes on or off
2. Get new equation from genotype
3. If equation is better, update the epigenetic line

Examples

Table 1: Performance Comparisons

Method	Problem	Success Rate	Mean Evaluations	Mean Effective Program Size
DLGP	$\ddot{x} = -1/2(0.75\dot{x} + 3x - F)$	83.33%	8.83E+07	145.11
DLGP+ESHC		100%	10.77E+07	96.65
DLGP	$\ddot{x} = -1.5(x^2 + 1)\dot{x} - x$	83.33%	9.20E+05	140.06
DLGP+ESHC		100%	9.27E+05	101.34





Next Steps

NREL CART3

Table 1: Variable Definitions

State Variables	Other Variables	Control Inputs	Disturbances	Constants
x_{FA}	rotor azimuth, ϕ	T_{gen}	wind speed, V	tower mass, m_{to}
x_{SS}		blade pitch, β		rotor radius, R
$\dot{x}_{FA}$				hub height, H
$\dot{x}_{SS}$				
$\ddot{x}_{FA}$				
$\ddot{x}_{SS}$