Concepts of Optimality and Evolution in Modern Plant Biology

Xinguang Zhu

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Identify driving forces underlining formation of certain biological phenomena

1. Curiosity →Observe biological phenomena, get statistical models showing the relationship between different variables
2. Define certain biological hypothesis or some “common” knowledge in biology
2. A range or **space of strategy set or phenotypes is defined**
3. Define the targets, or a parameter measuring the fitness of the strategy
4. Define each alternatives into a fitness payoffs, i.e. the choice of different strategies have different impacts on the fitness. The constraints and tradeoffs need to be considered.
5. Identify optimum and compare with experiments.
6. Suggest validation experiments and make new falsifiable predictions

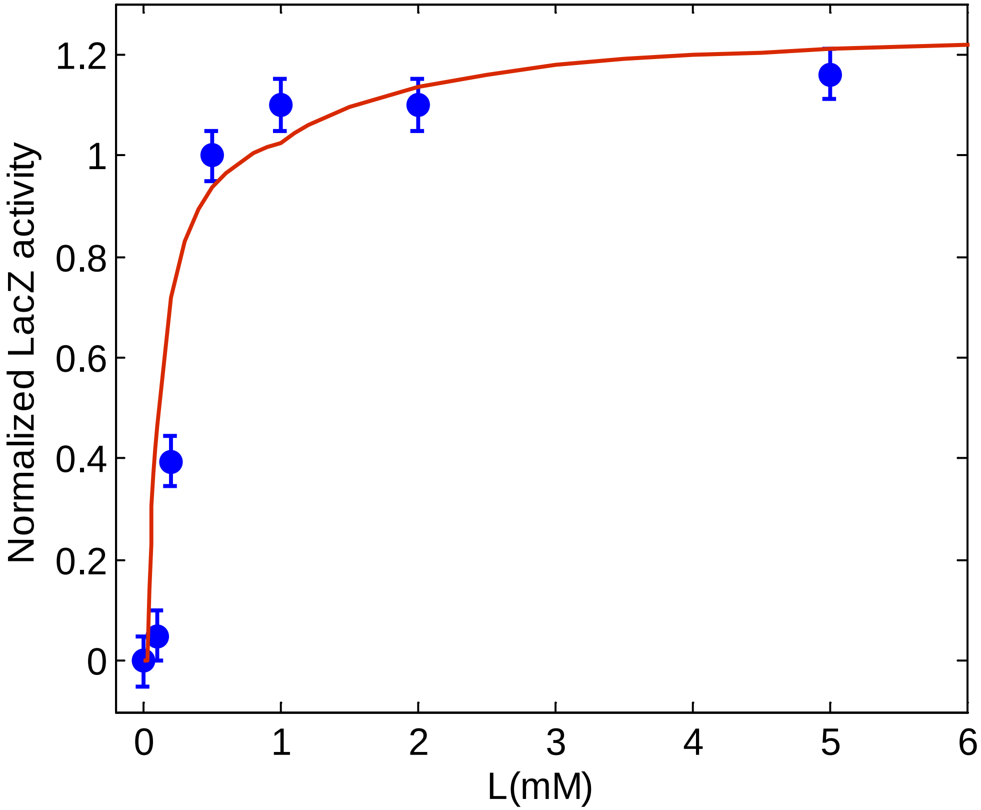
Parker and Smith 1990 Nature

Interpreting an optimality model

- “The final step in the optimality approach is to test the predictions against the observations. If they fit, then the **model may really reflect the forces** that have molded the adaptation. If they do not, we may have misidentified the strategy set, or the optimization criterion, or the payoffs; or the phenomenon we have chosen may not any longer be adaptive…“

Parker & Maynard-Smith, Nature (1990)

Adapted LacZ protein levels match predicted optima



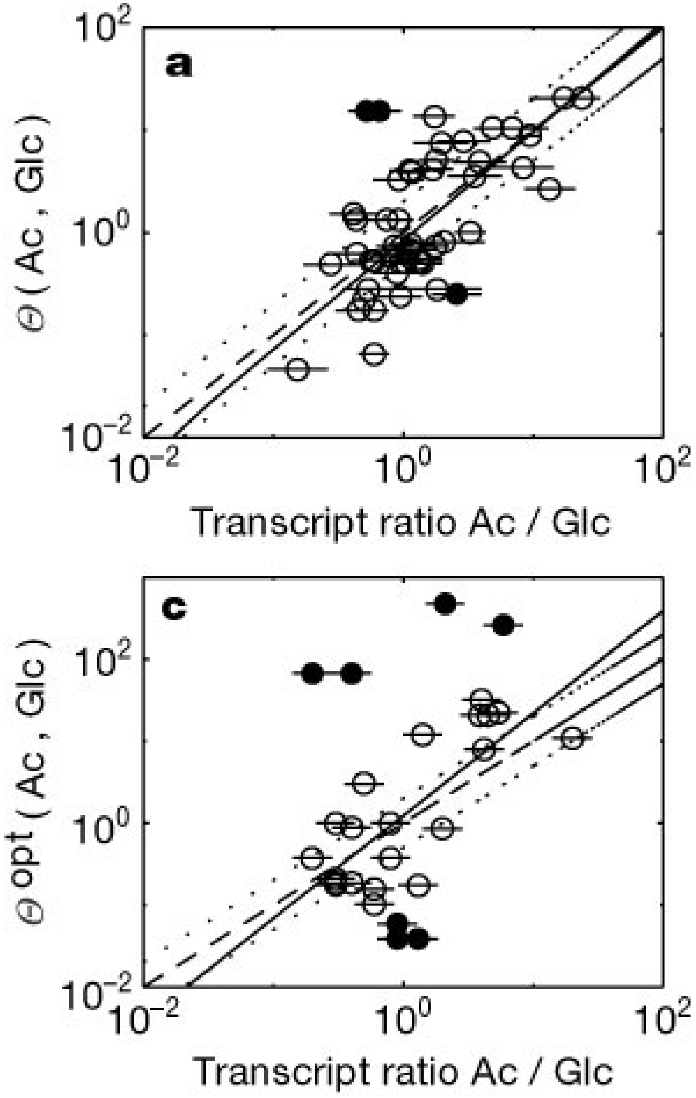
lacZ level measured after more than 550 generations

Dekel & Alon, Nature (2005)

Optimality operates at the genome scale!

As cellular control is achieved by genetic regulation, control effective flux (CEF) should correlate with messenger RNA levels.

Theoretical transcript ratios for growth on two alternative substrates:
$\Theta(S_1,S_2)=CEF(S_1)/\ CEF(S_2)$
in comparison with gene expression data
($r^2=0.6$)



Stelling et al 2002 Nature

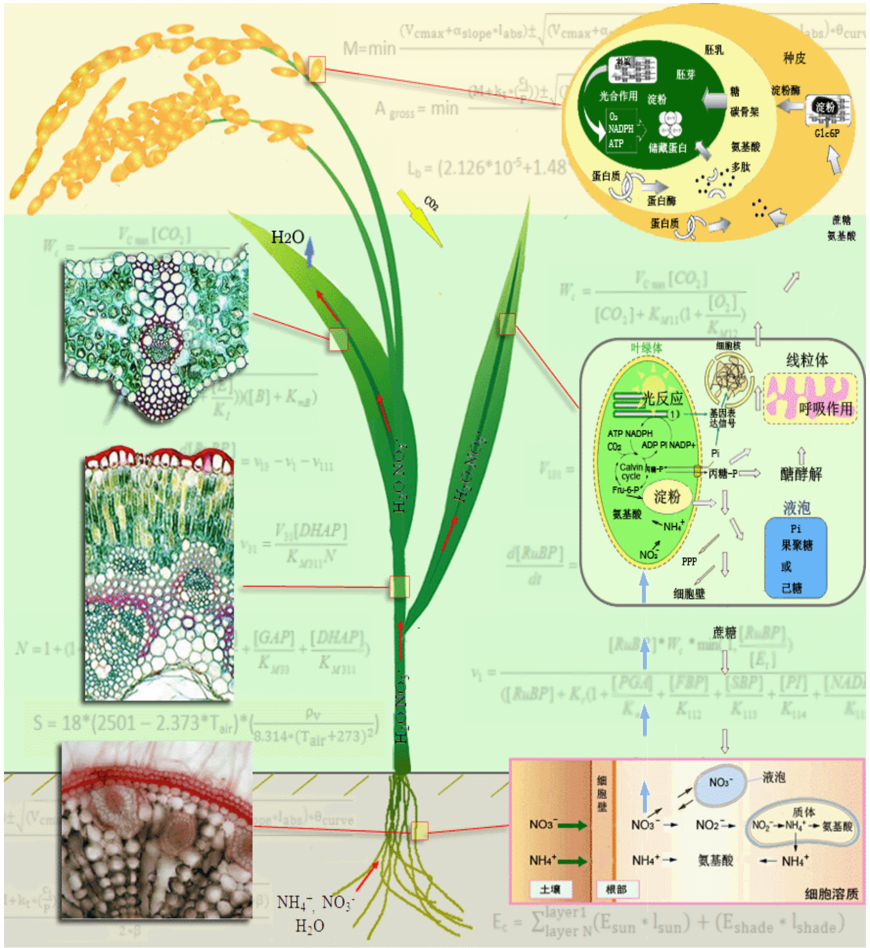
Key principles in design of biological network

- Simplicity?
- Robustness?
- Flexibility?
- Combinations of these three?
- Why evolution follows these rules (if evolution in deed does so?)
- Optimality (Does nature follow this rule?)

Evolutionary model as a basic tool in modern biology

- Optimality models test and sharpen our understanding (constraints, tradeoffs, fitness function)
- Defined structure that ensures rigor, sensitivity, resistance to external perturbations,
- Basic steps:
  - Evolutionary models
    - Obtain observations and derive relationships based on statistics
    - Model development (key step)
    - Enumeration of solution space for the model under different constraints based on certain model
    - Enumeration of model types for a particular problem (phenomena) under different constraints
  - Compare with biological data and gain insights on the fitness and cost function
  - Experimental validation of the model predictions

Testing the optimality, adaptation and evolution of photosynthesis and plant primary metabolism



Regulatory network

Metabolism

Leaf anatomy

Material allocation

Canopy architecture

Plant level processes

Managing & Engineering

DIVERSITY OF PLANT PHENOTYPES IN NATURE

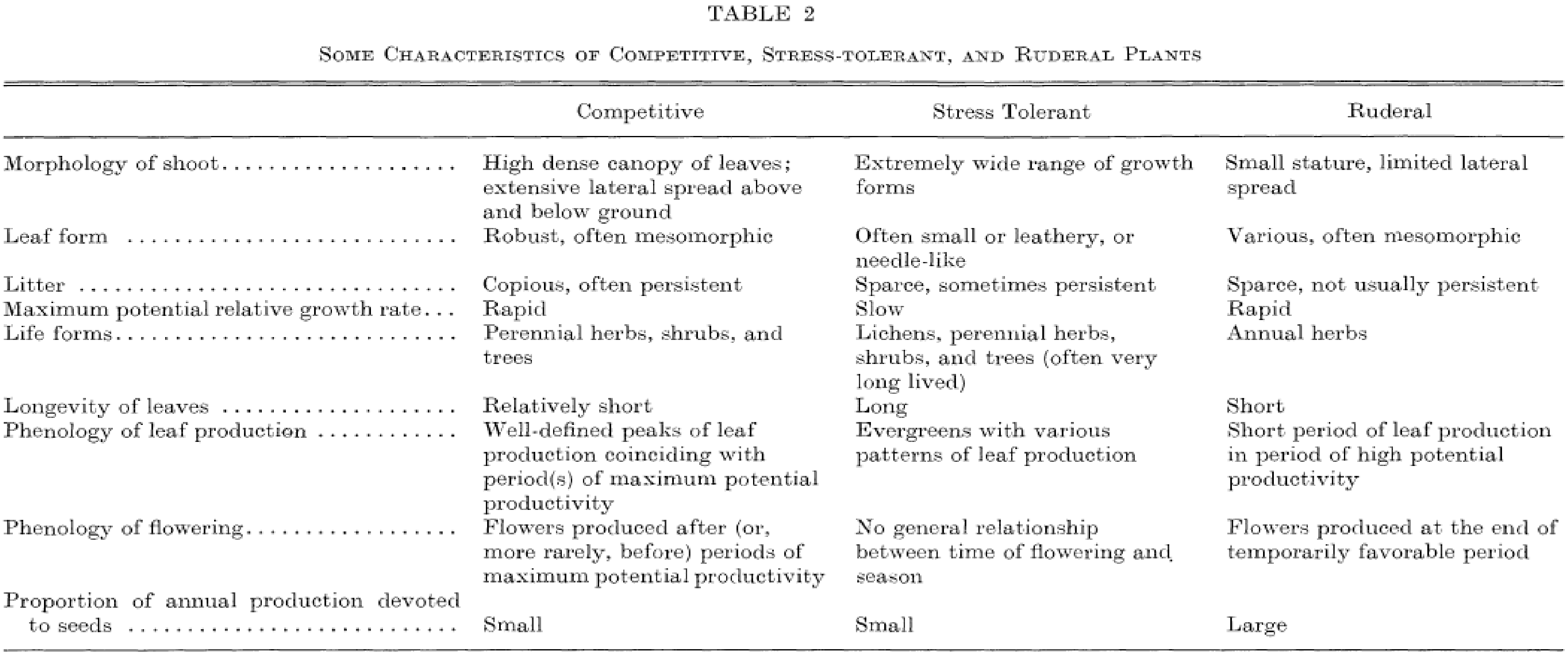
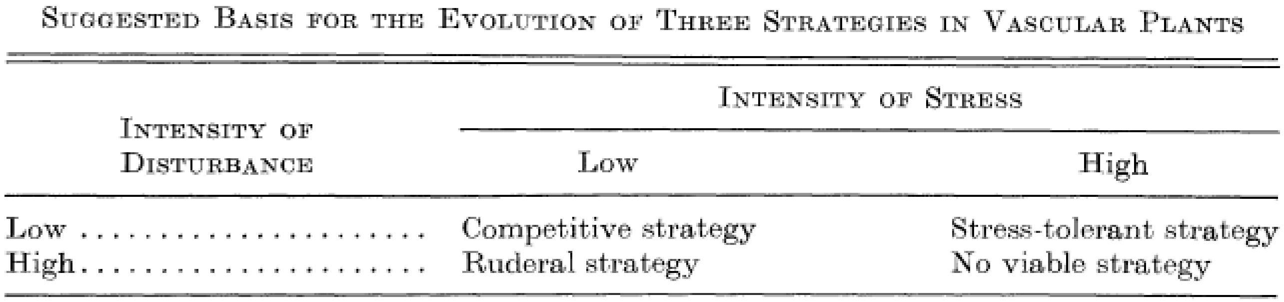


TABLE 2

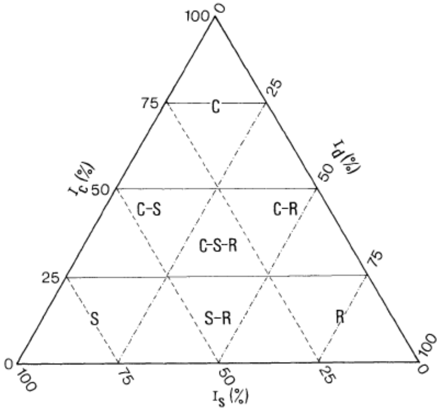
SOME CHARACTERISTICS OF COMPETITIVE, STRESS-TOLERANT, AND RUDERAL PLANTS

	Competitive	Stress Tolerant	Ruderal
Morphology of shoot	High dense canopy of leaves; extensive lateral spread above and below ground	Extremely wide range of growth forms	Small stature, limited lateral spread
Leaf form	Robust, often mesomorphic	Often small or leathery, or needle-like	Various, often mesomorphic
Litter	Copious, often persistent	Sparce, sometimes persistent	Sparce, not usually persistent
Maximum potential relative growth rate	Rapid	Slow	Rapid
Life forms	Perennial herbs, shrubs, and trees	Lichens, perennial herbs, shrubs, and trees (often very long lived)	Annual herbs
Longevity of leaves	Relatively short	Long	Short
Phenology of leaf production	Well-defined peaks of leaf production coinciding with period(s) of maximum potential productivity	Evergreens with various patterns of leaf production	Short period of leaf production in period of high potential productivity
Phenology of flowering	Flowers produced after (or, more rarely, before) periods of maximum potential productivity	No general relationship between time of flowering and season	Flowers produced at the end of temporarily favorable period
Proportion of annual production devoted to seeds	Small	Small	Large



SUGGESTED BASIS FOR THE EVOLUTION OF THREE STRATEGIES IN VASCULAR PLANTS

INTENSITY OF DISTURBANCE	INTENSITY OF STRESS: Low	INTENSITY OF STRESS: High
Low	Competitive strategy	Stress-tolerant strategy
High	Ruderal strategy	No viable strategy



Grime 1978 AB

Aspects needs Investigations

- Environment
  - Organisms functions in dynamic environments
  - Multiple environmental factors working together
- Scale issues
  - Multi-scale optimization (time and space), optimization only works at certain time and space.
  - Multi-targets optimization
  - Unit of evolution? Not all traits show adaption.
- Factors influencing fitness of biological processes
  - Reproductive success
  - Productivity
  - Ability to deal with environmental variations and random effects

Perspectives through Systems Level Analysis

- Models, capacity of the current knowledge in explaining existing phenomena.
- Understanding current biology
  - Importance of different parameters at different regions of the solution space
  - Importance of different parameters for current plants
  - Structural or parameter basis underlining the transition between different states
- Why nature evolved existing structure or parameters
  - Optimality
  - efficiency and cost
  - Structural and parameter basis of robustness and plasticity during evolution
  - Phylogenetics and
- These perspectives should be examined for models or processes at different spatial and temporal scales.

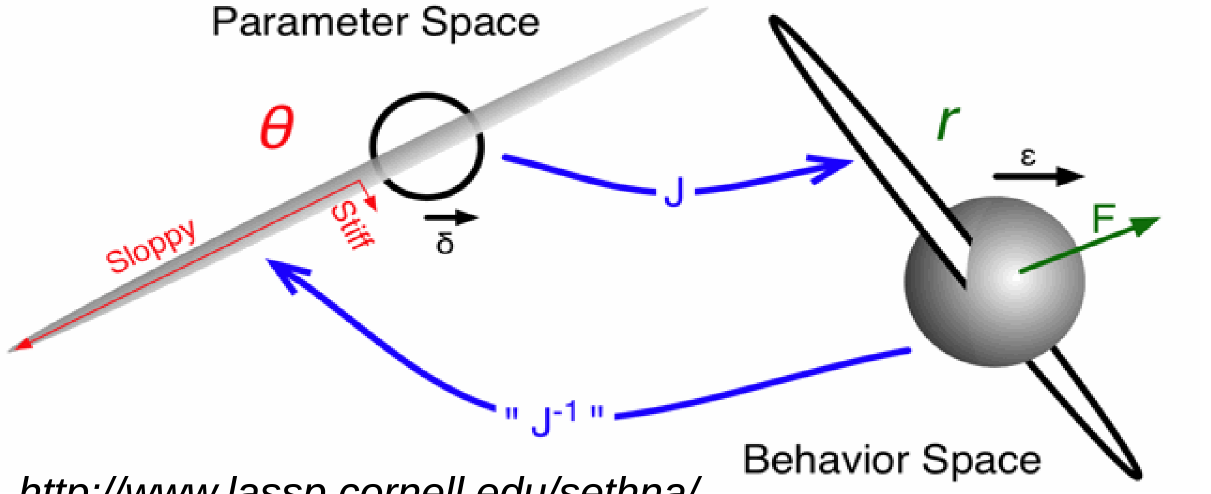
General models and specific models

- “General models have a heuristic function; they give qualitative insights into the range and forms of solution for some common biological problem. The parameters used maybe difficult to measure biologically, because the main aim is to make the analysis and conclusion as simple and as direct as possible”.
- “Specific models are designed to be applied quantitatively to particular species, and include parameters that can readily be measured. They are often modified (and more complex) versions of some general model, devised specifically for comparison with a particular set of observations. If the predictions of the model match the biological observations, we may hope that we have made correct assumptions about the nature of adaptations”.

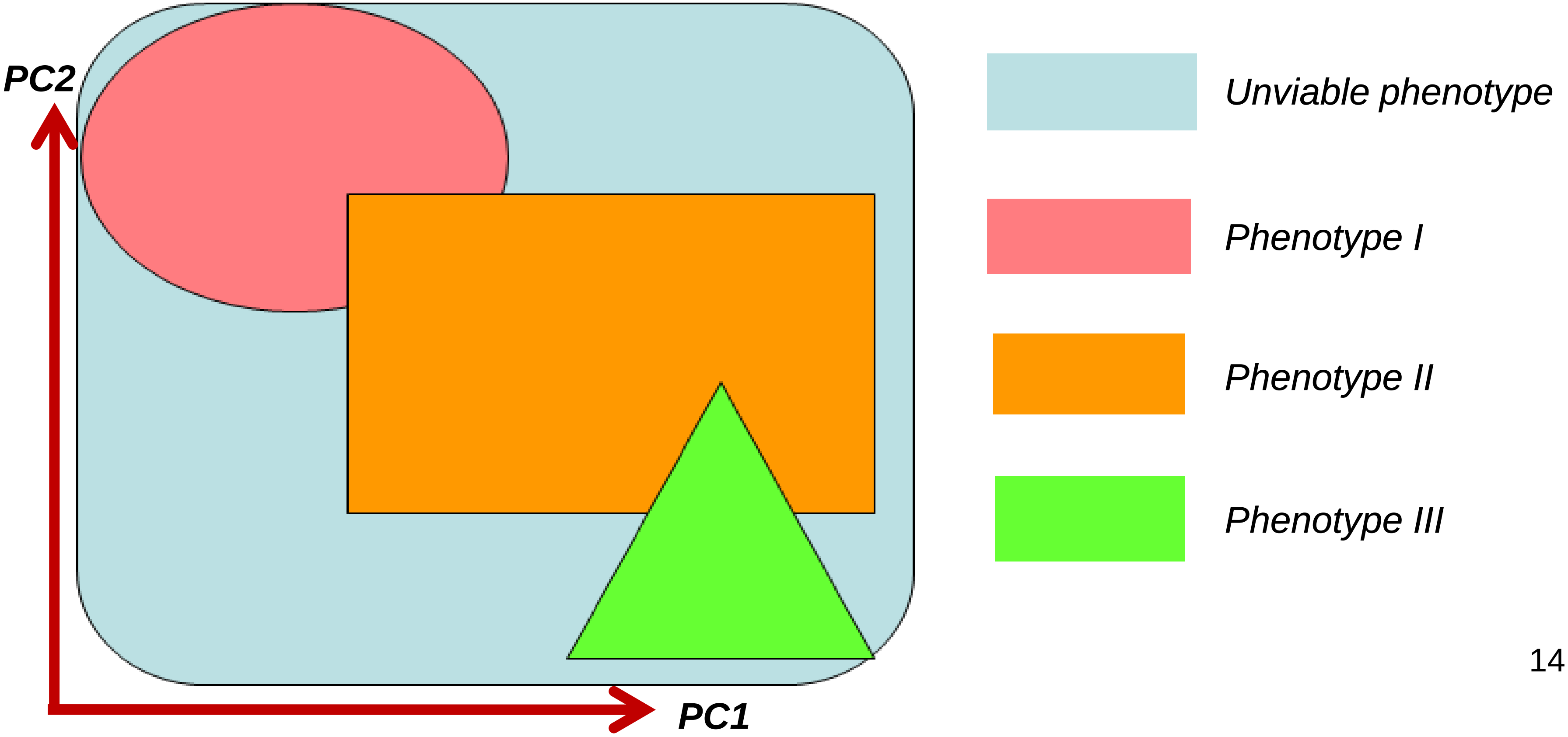
Parker and Smith 1990 Nature

How to identification of processes showing adaption/evolution

- No all traits are optimal
  - Phylogeny and development has major effects - frozen accidents (Rubisco?)
  - Random drift (bottleneck, founder effects etc) is often a dominant force (alleles can become fixed in a population in spite of natural selection, again Rubisco might be an example)
- Identification of adaptive processes
  - Molecular level
    - ratio between sense/nonsense mutation (Ancient evolutionary events)
    - Polymorphism around the site of mutation (recent evolutionary events)
  - Processes
    - Correlation of the changes of the process with changes in the fitness (most possibly reproductive success)



http://www.lassp.cornell.edu/sethna/



Resource Development Required for the Anlysis

- Models and databases
  - Basic numbers related to Cell (BioNumbers）
  - Basic numbers related to photosynthesis
  - Basic numbers related to photosynthesis at stand or ecosystem levels
  - Basic environmental parameters
  - **We need to develop a database to systematically document these information.**
- **Analysis techniques**
  - Course development: nonlinear dynamics

Key mathematical concepts required to conduct such research: Introduction to nonlinear dynamics (Zhu and Yang)

- **Basic concept**
  - Orientation (2 hours; Yang + Zhu)
  - ODE building and solving (2 hours; Yang)
  - Analysis of systems properties
    - Oscillations, limit cycle, and damped oscillations (2 hours; Yang)
    - Bifurcations, bistability and multistability (4 hours; Yang)
    - Chaos (2 hours; Yang)
    - Robustness (2 hours; Yang)
    - Introduction to complex systems (multibody system) (2 hour; Yang)
- **Biological application of dynamic systems theory in biology**
  - Stable switching (2 hours; paper: Novik and Wiener 1957; Zhu)
  - Robustness and sloppiness of biochemical networks (2 hours; Baikai and Leibler 1997; Zhu)
  - Ultrasensitivity (2 hours; Goldbeter and Koshland 1981; MAPK Cascade; Zhu)
  - Adaptation (2 hours; Cell paper; Zhu)
  - Specificity (2 hours; Hopfield 1974; Zhu)
  - Design principle (Savaguae UC Davis; Zhu)
  - The role of noise in biological dynamic systems (2 hours; TBD; Zhu)

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- 24. http://en.wikipedia.org/wiki/Richard_Lewontin
- Sloppy models: http://www.lassp.cornell.edu/sethna/Sloppy/index.html