

# Thermodynamic principles for system biology and the patterns of flower pigmentation

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## Research Article

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# Abstract

The thermodynamic principles for system biology are reviewed and formulated, and then basic patterns of flower pigmentation are interpreted. Main thoughts: 1) any biological trait (color or function of a cell) is logically related to a thermodynamic system (or physiological system, signaling network of the cell); 2) the striped, speckled and circle are three basic patterns of flower pigmentation, the development of flowers is an irreversible process;; 3) the patterns of flower pigmentation is formed in flower development; 4) the flower cells can change its color in a period of development and this process is controlled thermodynamically; 5) there is giant space of physiology within an organism and within it numerous thermal states can appear under different conditions. In this theory, the dominant inheritance means that a gene contributes great to the thermodynamic stability of a trait related system; different genes can be interacted or integrated thermodynamically according to their contribution to the stability of its related system. By combination of Turing theory and our views, complex patterns of pigmentation could be explained theoretically.

## Introduction

The beautiful flower of plants has attracted much attention from common people and many species of flowers have been cultivated domestically. The color of flowers is also an observable trait of plants and is widely utilized in our studying of biology in history. It is a well-established concept in genetics that patterns of flower color are controlled by genes (Griesbach, 2005, Harborne, 1978; Sobel & Streisfeld, 2013).

However, some beautiful flowers show different colors at different sites or parts of flower (flower pigmentation), which offer biological advantage to the plant for attracting pollinator (Dement & Raven, 1974; Yokoi & Saitô, 1973). The researches indicate that many genes have been involved in the production of such flower pigmentation (Thiede et al. 2011; Saito et al. 2015; Mizuta et al. 2010; Que et al. 1998; Ding et al. 2020; Yuan et al. 2014).

This feature cannot be fully explained by applying principles of genetics for it only studies the color changes between different individuals at same position of flower, and therefore it has no ability to describes features of color change on different sites within the same flower. So, the scientific mechanism for the production of such patterns is still lacking.

It is a well-established opinion that the formation of color flower results from the irreversible development of plant, but it is a challenging task to reveal its thermodynamic mechanism at molecular level (Gibbs, 1914; Lurié & Wagensberg, 1979; Zotin, 1972; Weber, 2009; Gordon, 2021; Igamberdiev, 2007; Chapman et al., 2016). In theory, this subject has been theoretically abstracted into developmental system (or evolution of biological systems, self-organizing system, the origin of natural order, the emergence of new things) (Weber, 2009; Gordon, 2021; Igamberdiev, 2007). Although many different approaches have been processed in field, none can account for numerous phenomena we have observed.

Alan Turing has studied biological patterns (now commonly called as Turing patterns) by principles of mathematics (Turing, 1952). Although this model has been revised many times, the underlying biological mechanism of it has never been revealed (Meinhardt and Gierer, 2000; Kondo and Miura, 2010; Sasai, 2013; Ishihara and Tanaka, 2018; Schweisguth and Corson, 2019).

As the development of protein signaling theory and thermodynamics of condensed state of matters (or complex thermal system), now it is possible to make us reveal its working mechanism by applying principles of thermodynamics (Zhao, 2012; 2016; 2017; 2018). Here, we use these principles to explain basic patterns of flower pigmentation. The analysis shows that the basic patterns of flower pigmentation can be well interpreted. In addition, the combination of our and Turing theory can give satisfied explanation to all biological patterns.

## Theory And Material

### 1. 1 Thermodynamic principles of system biology

At the beginning, we first review the basic and thermodynamic principles of system biology obtained in past times, and which act theoretical foundation for the discussion of patterns of flower pigmentation (Zhao, 2016; 2017; 2018).

**The color of a cell is associated with a special signaling network or a thermodynamic system** (Zhao, 2016; 2017; 2018). In view of this theory, a signal, such as enzyme or receptor activity, corresponds to a type of protein conformational state (or thermodynamic system), and any protein complex (or protein DNA complex, condensed matter in view of physics) represent a type of signaling network (physiological system), in which many types of signals can be inputted and integrated, finally many types of signaling activities can be outputted. The color substances are the product of this physiological system (signaling activity) (Li et al. 2014; Zhang et al. 2021). This makes us analyze patterns of flower color by applying principles of thermodynamics (Crapse et al. 2021).

**The formation of color cells from its original ancestor cell is an irreversible process in view of thermodynamics** (Lurié & Wagensberg, 1979; Zhao 2016). When a color cell is produced in the irreversible process of development, it will remain its trait forever. It means that color cells show epigenetics (Goldberg et al., 2007). This principle gives a satisfied explanation to the stability of flower color patterns.

**The distribution of different color cells can be described by partition function of complex thermal system (or condensed mater)** (Zhao, 2012, 2017). As development is an irreversible process and the principles of equilibrium thermodynamics can be only validated in a limited range of time and space in which the thermal equilibrium can be reached, the first task of us is to ascertain that in which range the equilibrium principles can be applied. Fortunately, the principle of equilibrium thermodynamics is at least validated in the formation of color cell in its development. At present, the thermal parameters of color cell cannot be

measured directly and experimentally. but we can judge it by external trait of flower, such as quantity of color cells and position of color cells (color spot).

**The production of a color cell in the development results from complex thermodynamic integration of diversified factors.** The bioinformation of gene, environmental factors (temperature and concentration of oxygen), the nutrition state, and products of other cells can be interacted or integrated at diversified levels of hierarchical structure of signaling network.

**Three basic patterns of flower pigmentation are striped, speckled, circled flower.** All other complex figure can be considered as complex combination and varies of these patterns.

## 1.2 Thermodynamics

Although the concept of thermodynamic stability of a color cell related system is very clear, we cannot measure it experimentally by applying experimental methods of traditional thermodynamics. Thus, we adopt different method to do so.

Firstly, we deduce some predictions (patterns of flower pigmentation) by applying basic principles of thermodynamics. If we can find it in nature, the principles will be approved. Secondly, when the principles are tested, we can use biological trait or observable features to judge or deduce the general profile of stability of color cell related system.

The stability of color cell related system of physiology is changed with time and space, in order to analyze its trait, we should firstly simplify it. In a simple model, we only study the role of distance (or radius) from Flower Pistil to desired position. We can further conclude that: In the circle line round the flower Pistil, if there is no color alteration in this line, the thermodynamic stability of color related thermal system for all cells is same.

If an individual shows two colors at different parts and at any parts it shows one color, it belongs two states distribution. The principle of it can be expressed in figure 1.

$\Delta G$  is the stability of color related system of physiology,  $r$  is the distance between reference point and site in flower, the yellow and red lines represent hypothesized stability line of color cell related system.  $p$  is the probability of color cell.

In figure 1, the stability lines of color cell related systems are the hypothesized profile and actual they are not straight, but curve, but this does not affect our understanding of it. The  $P$  can be calculated from stabilities of red and yellow color related system by principle of partition function of condensed matter (Zhao, 2012, 2017). If the stability of a color system of the cell is more stable, it dominates the color of individual cell. If the stability of two types of color systems of cells is almost same, the population of two types of color cell can be distributed according to its thermodynamic stability, the motley area may appear.

### 1.3 Theoretical Prediction

If the flower color is related to a thermal system and production of flower pigmentation is controlled thermodynamically, we should predict following phenomena:

1. There is no standard figure for flower pigmentation, the flower pigmentation will vary from flower to flower because thermal distribution of color cell shows randomness. Or in other words, there is no position within flowers which show fixed color. The size and position of flower pigmentation vary.
2. The figure of flower pigmentation is sensitive to temperature, genes, drug, environmental factors which influence the thermal state of color cells. The size and position of speckle, color line in flower will also vary.
3. The color line and population of color speckle will change with the environmental change.

### 1.4 Materials

The flower of *Mirabilis Jalapa L* is selected for it is common over the world and it show different color at different parts in same flower. It is the hybrid of yellow and red of *Mirabilis Jalapa L*. Normally, most of its flower is yellow and little are red.

## Facts And Discussion

### 2.1 *Mirabilis Jalapa L*

**Speckled and striped flower.** The photos of flowers of *Mirabilis Jalapa L* are taken in Beijing Park and it can show yellow or red color at different parts of the flower. The results are shown in Fig. 2.

The results are shown in figure 2.

The Fig. 2a and 2b are the striped flower. The color area is lasted from bottom to out edge of the flower. It forms at early embryonic stage of flower development. The  $1/5$  (or one *Petal*),  $2/5$ ,  $3/5$ ,  $4/5$ ,  $1/10$  flower and their combination can be commonly seen. There are many types of striped flowers and the striped band may theoretically be  $1/(5 \cdot 2^n)$ ,  $n$  is positive integer, flower, but it is very difficult to judge it when  $n$  is larger than 2. When a red cell appears at 5 cells stage in flower development, it will grow into one *Petal* (or  $1/5$  of whole flower).

The big speckled flower is shown in Fig. 2c. It forms at middle embryonic stage of flower development. It must indicate that the position and size of red speckles vary from flower to flower and no two flowers are the same. This property expresses the randomness of thermal distribution among different physiological states.

The small speckled flower is shown in Fig. 2d. It forms in later stage of flower development. When color spot is fine, the motley area (or mixed area) of colors may appear.

**Similar type of flower pigmentation appears in same twig or individual.** As the cell physiological state varies in development and flower pigmentation is controlled thermodynamically, the thermodynamic properties of all cells of a twig are similar, the similar types of flower pigmentation should appear at one twig. This view is true. The results show similar type of flower pigmentation appear in one twig or individual (Fig. 2a and 2d).

**For *Mirabilis Jalapa* L, the controlled factor for flower pigmentation is not related to flower development.** This conclusion can be judged by facts: for an individual, flowers show same color in a same twig, and show different colors in different branches (or twig). It indicates that the gene for color production is not the necessary gene for flower development. It is same with other report (Yuan et al. 2014).

The Fig. 3a is an individual of plant which shows different color flowers at different twigs. The Fig. 3b is the working mechanism for that phenomenon. Briefly, the physiology of plant varies in growth, and it makes the fluctuation of stability of color related system. When new branches grow from a point of the plant, the stability of color related systems will determine its development. If it is under controlled by red color cells, it will develop into red flower, and vice versa. The different branches have different stability curves. It must be pointed out that the different branches of plant have different stability curve and it is the hallmark of irreversible thermodynamics. The range of stability of color related systems constructs a giant space of physiology for an individual and in which a cell can develop and select its traits within this space.

**The patterns of flower pigmentation are temperature sensitive.** On 5, July, 2021, the temperature of Beijing is about 24–32°C, we only see one flower with pattern of Fig. 2d. However, it become more and more at Sept, 2021 (temperature is 16–26°C). It has reported that formation of cellular organs can be influenced by D<sub>2</sub>O (environmental factors) (Takahashi & Sato, 1982). They are powerful evidences for the concept that biological systems represent a thermodynamic system, and not the dynamic system.

## 2.2 Others flowers

**The change of color line in space.** The *hibiscus* has two species. One show white flower with dark red area at bottom of flower (Fig. 4b), and one show light red with dark red area at bottom of flower (Fig. 4a). The light red and dark red represent two different signaling activity.

Compared Fig. 4a with 4b, we see that the dark red area is expanded and position of color line is changed. It arises up from the cooperation of signaling activities between light and dark red related system. It must be pointed out that this figure is taken in July, Beijing, China. When it is observed in September, the Fig. 4a is changed and the dark red area is same as that of Fig. 4b (data not shown).

**The change of population of color area in flowers.** The *phalaenopsis* is most cultivated over the world and many varieties have been developed. Figure 5 show three different flowers of different strains.

From Fig. 5, we see that the population of red color area is changeable from flower to flower, and even within a flower. It is the hallmark for thermal distribution.

**Complex features of color speckle.** The color speckles vary in size and shape. In most cases, it may be circle (Fig. 5), in some cases, it may be a short line (Fig. 2c). It is reported that patterns of flower pigmentation are associated with cell communication (Que et al., 1998; Albert et al., 2021; Morita & Hoshino, 2018; Muñoz-Falcón et al., 2011). The reason is that not all cells of plant are completely independence and the communication between different cells has role in the development of color speckle. In this case, several or many cells, not a cell, should be considered as basic unit of thermal fluctuation. But this revision will not change the basic principles for the production of color speckle.

**The change of flower color area by virus.** The well-known example is Tulipa virus which affect or induce the patterns of flower pigmentation (Nakayama, 2014). It indicated that a viral protein act regulating factor for flower pigmentation.

## Thermodynamic Revision Of Turing Theory For The Formation Of Complex Patterns

Our theory has revealed the thermodynamic mechanism of the simple and basic patterns of flower pigmentation. The three basic patterns of flower pigmentation have not been included in Turing patterns, which express complex patterns of biology proposed by Turing in field of mathematics (Turing, 1952). Although the rightness and applicable scope of it remains questionable, it is the best and more complete theory about the formation of biological patterns (Schweisguth and Corson, 2019; Meinhardt and Gierer, 2000). In field of biology, several problems of it are difficult to be answered: 1) the stability of biological patterns; 2) the size and positions of pigmentations is changeable in the growth of individual; 3) if there is big difference of molecular diffusions of biomaterials, the flower or organism will grow differently at different area, and this does not agree with common knowledge of biology; 4) the nature of morphogens. In fact, the Turing theory can be naturally revised according to our theory. All these difficulties of Turing theory can be easily overcome If we assume that:

- 1) **the state of signaling network of a cell acts as morphogens, the concept of Turing theory.** The thermodynamic stability of biological patterns is guaranteed by a biological structure.
- 2) **The dynamics properties or thermal fluctuation of the thermal system, interaction between different cells, could replace (or substitute, represent) the role of diffusion process of Turing theory.**
- 3) **The inhibitor and activator of receptors are widely seen in signaling network, and they can take role of feedback mechanism or catalyzing processes in Turing theory.**
- 4) **The flower (animal) patterns (or Turing patterns) are generated at a point of time in the irreversible process of the development.** When the patterns are formed, the size of speckles can be enlarged, the position and shape of speckles can be changed, but the relations among different speckles remains unchanged. So, when the fingerprint of human is formed in a period in development, it can remain its general patterns forever.
- 5) **The gradient of thermodynamic stability of a thermodynamic system (signaling network) induced by many factors acts the chemical source for the chemical flus among different areas (or cells) of the**

## biological organs.

Thus, the processes discussed by Turing is one essential step of patterns formation. This revision of Turing theory can account for all biological patterns although the specific situation for the formation of every pattern varies largely and should be studied carefully in future.

## Conclusions And Theoretical Explanations

Overall, the features of flower pigmentation of *Mirabilis Jalapa L* and others can be quantitatively explained by thermodynamic principles.

In this view, the so-called dominant inheritance in genetics is that the gene contributes much to the thermodynamic stability of its trait related system, and latent inheritance is that the gene which contributes little on the thermodynamic stability of its trait related system, the gene interaction represents the fashion of information integration on the stability of trait related system. According to this theory, the additive effect of genes can be observed if these genes act at same levels of hierarchical structure of signaling network, the epistatic dominance occurs when different genes act on different levels (Carlborg & Haley, 2004). Thus, the fashions of gene interaction can be easily understood by this view.

Although environmental factors have great impact on the stability of color related system, the gene acts the main signaling activity (information) in vivo in the controlling of the stability of color related system of cells, thus hybrid is powerful tool to alter the stability of cell color related system. In fact, some well-known strains of flower, such as striped rose, striped and spackled Japanese morning glory are all obtained by this method (Muñoz-Falcón et al., 2011; Nakayama, 2014).

## Declarations

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## Figures

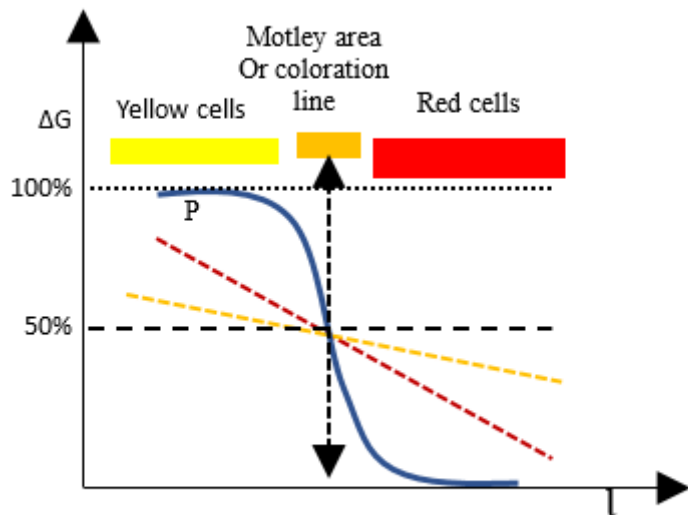


Figure 1

Two state distribution of color cells



## Figure 2

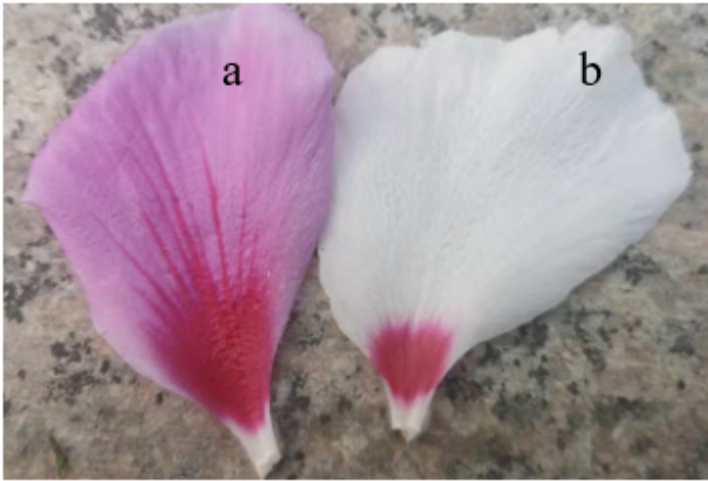
Different patterns of flower pigmentation



## Figure 3

The physiology of flower

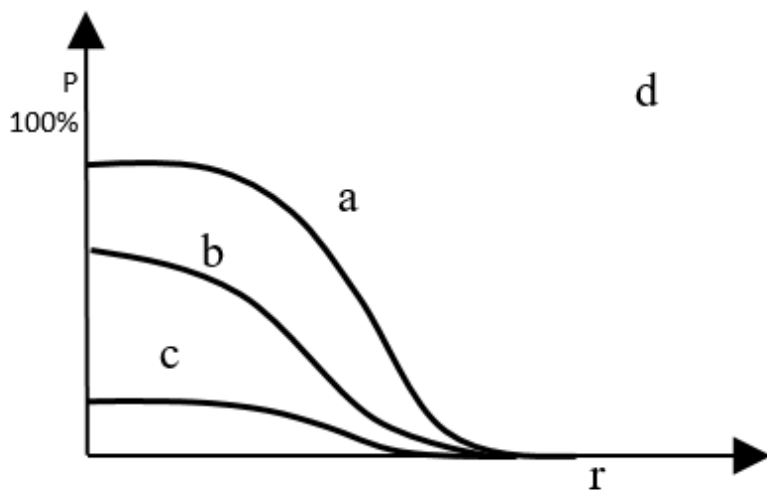
$\Delta\Delta G$  is the stability difference between yellow and red color related systems,  $x$  is the distance of desired position from reference point of the plant. The red line represents the hypothesized (or simulated)  $\Delta\Delta G$  along the red branch, the yellow line represents the hypothesized (or simulated)  $\Delta\Delta G$  along the yellow branch.



**Figure 4**

The change of color line within a flower

Two *Petals* of *hibiscus* flower from different trees are shown.



**Figure 5**

*Phalaenopsis* flowers.

The  $p$  is the population of red color cells,  $r$  is the diameters of flower. Figure 5d is the simulation of color density of red cells.