GEOMETRIC MOBILES

几 何 动 艺

——魔　摆

Mooson Kwauk
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献给中国的青少年（代序）

我一生从事化工研究，现年逾七旬，对过去能做的工作，已感心有余而力不足。近年来我逐步转向力所能及之事：除了写书改稿，我开始做“几何动艺”。对我的动艺，我仍然采用多年来所熟悉的方法：构思—设计—制作。我的作品数早已过百。许多朋友欣赏这些风动作品，其中不少人认为何不将这套颇能启发智力的方法传授给青少年。

“几何动艺”的构思要求立体的思维、运动的设想以及一定程度的美感。设计要求运用简单的力学分析，主要运用几何、三角、代数等中等数学进行数学模拟，定量地指导自己如何动手。制作的物质要求不高：一般的手工工具和易得的材料。但另一方面，制作要求精确的手艺、耐心细心和不断地去想办法。

“启发智力”对我是一种启发。多年来，我深感我国的青年科技工作者创造能力不强。这与我们的教育有关：许多老师向学生传播知识，而很少启发他们如何适应社会、经济、资源去用自己的头脑想办法，改造自然、创造工艺、方法或制品。我不能说，“几何动艺”能给青年带来多大能力，但只要一旦他们能被自己的创作所吸引，他们将不断给自己创造练习“构思—设计—制作”的机会，形成这种习惯。

“几何动艺”对我从自娱开始，今后可能成为帮助青少年成长的一种社会活动。我很感谢观赏我作品的朋友们的启发，特别是边东子同志。他帮助我组织有关活动，寻找制动艺的材料，并取音译义，将我英文原著命为“魔摆”，由化学工业出版社得以出版。

Autobiographical Notes of Author

1920 born Hanyang, Hubei Province, China; third son of British trained engineer, Z. U. Kwauk, who produced iron and steel at Hanyeping Ltd., the only ferrous metals maker in those days

1943 B.S., chemistry, University of Shanghai

1947 M.S, chemical engineering, Princeton University; noted in dissertation research the distinct behavior of fluidization of solid particles with a liquid and with a gas, for which the designations, "particulate" and "aggregative" were proposed respectively

1946-1947, 1952-1956 Hydrocarbon Research Inc., New York: process development in coal gasification, air separation, gas purification, gaseous reduction of iron ores; 3 U.S. patents

1948-1952 Coca-Cola Export Corporation: built first bottling plant (New Dehli) in India; headed laboratory in New York; received Chesterman Award in 1950 of American Bottlers of Carbonated Beverages for analysis of carbonation

作 者 简 历

1920 出生于湖北汉阳，留英工程师郭承恩的三子，郭承恩当时于汉冶萍钢铁厂负责钢铁生产

1943 毕业于上海沪江大学化学系

1947 美国普林斯登大学化工硕士，在论文研究中首次观察到液/固和气/固流态化的差异，分别命名为“散式”和“聚式”流态化

1946-47, 1952-56 纽约碳氢研究公司，开发煤气化、空气分离、气体净化及铁矿气体还原工艺；获三种美国专利

1948-52 美国可口可乐公司，于新德里建造印度的第一个可口可乐工厂；负责纽约总部实验室；获1951年美国汽水同业会的彻斯德曼奖(碳化分析)

1956-date Institute of Chemical Metalllurgy, Academia Sinica: professor, director 1978-1986, emeritus director since 1986; fluidized roasting of oxidic Chinese iron ores for upgrading, for separation of nonferrous metals and for powdered iron; fluidized leaching and washing of ores for winning nonferrous or rare metals; proposed "generalized fluidization," and other basic concepts; latest books: *"Idealized and Bubbleless Fluidization,"* 1992, Science Press and Ellis Horwood; *"Fast Fluidization,"* 1994, Academic Press; awards -- twice, National Natural Science Award, second class, 1982 and 1990; International Fluidization Award, 1989, Canada; elected 1980 Member, Academia Sinica; visiting professor, 1986-87 Virginia Polytechnic Institute and State University, 1989 Ohio State University; 1984 Davis-Swindin lecturer, Loughborough; 1989 Danckwerts lecturer, London

1956-今 中国科学院化工冶金研究所研究员、所长(1978-1986)、名誉所长(1986-今); 中国氧化铁矿的流态化焙烧(富集, 分离有色金属, 制金属铁粉); 流态化浸取和洗涤(提取有色和稀有金属); 提出"广义流态化"及其有关概念; 近年著作:"理想和无气泡流态化"(1992), 科学出版社和 Ellis Horwood; "快速流态化"(1994), Academic Press; 获奖: 二次全国自然科学二等奖(1982 和 1990); 国际流态化成就奖(1989, 加拿大); 1980 年当选为中国科学院院士; 访问教授(1986-1987 美国弗吉尼亚工业大学, 1989 美国亥海亥州立大学); 1984 英国拉夫保罗 Davis-Swindin 演讲; 1989 英国伦敦 Danckwerts 演讲

1950 married to Huichun Kwei, M.S., social work, Boston University; son, Weimin, software analyst, SCI Corp., Huntsville, Alabama; daughter, Reimin, consultant, Information Management Technologists, Inc., Malvern, Pennsylvania; son, Xianmin, chemical engineer, Sverdrup Technology, Inc., Sunnyvale, California

1950 结婚, 爱人桂慧君为美国波士顿大学社会工作硕士; 长子伟明, 美国 SCI 公司; 女儿瑞明, 美国 MIT 公司; 次子向明, 美国 Sverdrup 公司

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HOW DID I BECOME INTERESTED IN MAKING MOBILES

我是怎样开始制作“几何动艺”的

As a young boy I was taught by my father how to make kites. He was an engineer, and as all engineers do, he had his own ideas of making kites, apart from accepted practice. Some of the kites would fly, and some would not. This predated aerodynamics as an established discipline in engineering, and the then hobbyist rarely went to the extreme of giving serious studies to what he was doing.

I have since become interested in wind-driven toys and devices. Kites were used in China for military purposes as well, such as releasing lethal missiles from high vantage points onto the enemy or reconnaisance by hoisting observers up in the sky. A toy which is made even to this date is the hot-air driven circus lantern, with acrobats painted on a paper cylinder illuminated from the inside by a lit candle, which also rotates the cylinder by propelling a paper windmill located at the top. Sometimes the acrobats are replaced by figurines of spear-bearing cavalliers attached to the windmill, thus imparting even more realistic animation.

Windmills are sometimes used in the Chinese countryside for power, just as they are in Europe or other parts of the world. But all these, toys and devices used in productive activities, have been handed down from generation to generation with the barest attention to innovation or even improvement. To the casual observer they may seem novel, but for those who have lived with them, they are mere morsels of an old institution, established and somewhat mundane.

The Chinese also possess the inclination to pursue the abstract. For example, the Chinese characters have their origin in ideograms which are pictorial representations of objects, motion, or even ideas. So, as I grew up, I became interested in engraving seals using archaic Chinese script, and

在我幼年时，父亲教我做风筝。他是个工程师，对风筝的制作有自己的想法，而不循传统。他的风筝有的能飞，有的却上不了天。这远在航空工程学科建立之前。当时的业余爱好者也很少用科学方法认真研究他们的作品。

从此，我对风动玩具和设备有了兴趣。风筝在中国曾用于军事，当作侦察和投射的工具。另一个具有中国特色的风动玩具是走马灯，用点燃蜡烛的热气进行驱动。走马灯可用绘图或小件模型装饰，使其运转更生动迷人。

中国南方农村田野中常可看到风车，用于输水、碾米、磨面。这和一些欧洲国家相同。可是这些风动工具大都代代相传，对其进行研究的人并不太多。外来的游客往往见之好奇，但当地的居民早习以为常。

中国人习惯于对现象的抽象。中国的文字就始于像形，从代表形态逐步发展至代表概念。我从幼年成长，逐步对刻图章感兴趣，当然采用的都是篆字。后来，又常用英文字母为朋友设计人名首母的母标，为学术会议设计会标。

later, in designing and making monograms for friends and logos for conferences and books.

Mobiles, in their modern sense, caught my attention when I lived in the United States in my younger years. Sporadically I made weak attempts at designing and making mobiles, but my efforts proved to be rather futile, especially in my later years, when as director of research, I felt myself almost constantly on call during all my waking hours. Now that I am retired from active duties, I begin to have the luxury of leisure and have taken up mobile-making as a continuation of what I relinquished in my younger years.

我年轻时旅居美国期间即注意到几何动艺。偶尔我也做些动艺，但从未认真地去设计和制作。特别我成年后将绝大部分精力投于科研工作，没有时间搞业余爱好。现在我已年迈，能支配一些自己的时间了，于是又拣起年轻时的爱好。

Since my retirement as director of research in late 1986, I started a somwhat systematic effort at making mobiles. In about two years I had accumulated about two dozen prototypes of my own design, and had formulated a set of rules, or "constraints," for conceptualization, design, mathematical modeling and construction. From the ample notes that I kept for what I had made, I wrote, in early 1989, the first draft of this book, and in 1993, I printed 100 copies of my 10th draft. The present 11th draft contains improvements in text and figures, additional examples of design, as well as new ideas on balancing and stringup of mobile members.

於 1986 年从负责岗位退下以后，我开始有系统地制作几何动艺。在初始的两年中我制作了二十多个几何动艺的模型，并对如何形成概念、如何设计、如何进行数学模拟及制作，提出了一套制约条件。同其它研究工作一样，我对制作几何动艺保存了不少文字记录，於是到 1989 年我已写成了本书的初稿。於 1993 年我在内部出版了我的第十稿。本书为第十一稿，包含了对文字和制图方面不少改进，增加了设计内容，并提出了如何平衡和串联动艺的新方法。

As I see it, the attraction of mobiles lies in their abstraction in shape, irregularity in motion and yet a deterministic approach in design. Whenever mathematical formulation is possible, mobiles represent the objective realization of a designer's endeavour at creating shape and motion in harmony with given sets of constraints.

对我来说，几何动艺的魅力在于抽象的形状、不可测的运动以及设计者对形状和运动的全局控制能力。特别是数学模型更可使设计者定量地掌握他所构想的形状和运动。

Coming from a nonartist background, and, perhaps, from a different culture, I came to know the names of the accomplished meisters in mobile-making very late in my life, and began to admire the creative genius of Alexander Calder and George Rickey only during my very recent visits in the United States.

我不具什么艺术背景，且生长在中国，对西方的动艺大师，如 Alexander Calder 和 George Rickey, 仅在近年去美国访问时才见到一些他们的作品。

PROPOSED CONSTRAINTS

In developing the mobiles described in this book, certain self-imposed rules have been observed to accentuate the concept of shape and motion in space:

- shapes of mobile members to be geometrically definable
- materials limited to rod/wire and plate/sheet with no extraneous ornamentation except high-quality surface finish
- jigsaw layout of mobile members to minimize waste of materials and to further highlight the uniqueness of geometrically definable members
- balancing of mobile members to be modeled mathematically which is facilitated by the use of geometrically definable members, thus adding another diemension to the aesthetics of mobile-making, namely, intellectual fulfilment
- all mobiles driven by normal air current indoors – preferably by body movement or breathing of an observer standing nearby – and none to be engineered to withstand gale or hurricane outdoors

制约条件

我对动艺的设计和制作，自定了一些制约条件，以突出其形状和运动的构思：

- 形状必须属在几何上可述
- 材料限于棒、丝形或板、片形，除了磨平抛光外，不加表面修饰或上色
- "七巧板"似地裁切下料，尽可能不浪费材料，组件能拼回原状
- 动艺部件的平衡须循数学模拟，强调设计的科学性和普适性
- 室内陈列，要求观看者的呼吸和身体运动足以启动作品，不考虑能否承受狂风的工程措施

PHYSICS

物理

A mobile normally consists of a train of similar members, and the mobile designer is concerned with two principal aspects of the physics of a mobile train:

- statics for balancing single members and their mathematical formulation
- dynamics of swing of the members

Static balancing of any single member of a mobile train is determined by two points: the point for the center of gravity (CG) of the member and the point of support (S) at which the member is suspended from above or supported from below. Figure Ph-1.1 shows a member supported *at* the center of gravity, S = CG. This is a meta-stable state, for the member can be revolved to any position in space around S=CG as the center. Figure Ph-1.2 shows the unstable state for which a member is supported at a point directly *below* the center of gravity. Under this condition, the member will turn 180° to reverse the relative position between S and CG. Figure Ph-1.3 shows the stable condition when S lies *above* CG, at which the member will assume the horizontal position shown so that S remains directly above CG. If, however, S is at an angle θ toward the upper left hand side of CG, then the member will assume an inclined position θ from the vertical.

If a member, stably balanced at a horizontal position, shown in Figure Ph-2, is displaced by an outside force through an angle θ, then there will be a torque equal to ($l\, m\, g \sin\theta$) tending to restore the member to its original position when the outside force is released. Here l is the distance between S and CG, m the mass of the member and g the gravitational constant. It can be seen that the farther is S removed from

一件几何动艺由一系列类同或类似的组件构成，其设计需考虑二个物理要素：

- 组件的静态平衡及其数学模拟
- 组件的动态运动

组件的静态平衡取决于两个点：重心 CG 和悬挂点 S 。图 Ph-1.1 表示组件于重心悬挂，即 S=CG 。这是一种介稳态：组件可以 S=CG 为中心而转动。图 Ph-1.2 表示组件于重心下悬挂。这是一种不稳态。在这种情况下，组件将自动倒转 180°，使 S 位于 CG 之上。图 Ph-1.3 表示悬挂点 S 位于重心 CG 之上。这是一种稳态。经过任何扰动，组件会回到 S 处于 CG 之上的位置。如果 S 位于 CG 之上且与垂直方向成 θ 斜角位置，那组件将以 θ 角倾斜。

如果一个原来处于平衡位置的组件，受外力作用移至倾斜角 θ 处，在除去外力后，有一个等于 $lmg\sin\theta$ 的力矩使之恢复原位。式中 l 是悬挂点 S 和重心 CG 之间的距离， m 是组件的质量， g 是重力常数。从图 Ph-2 可见， S 和 CG 之间的距离 l 越远，恢复力矩也相应越大。

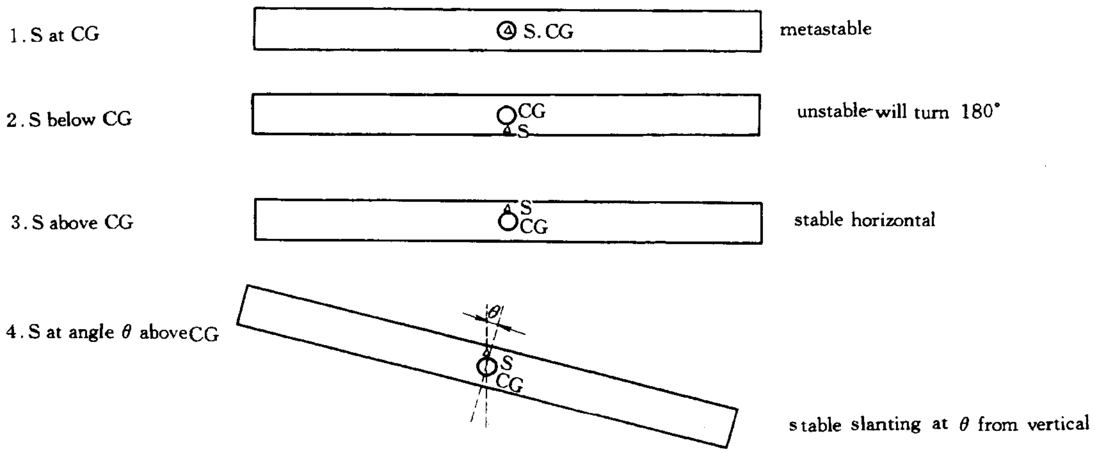

Figure Ph-1 Static Balancing of a Single Mobile Member

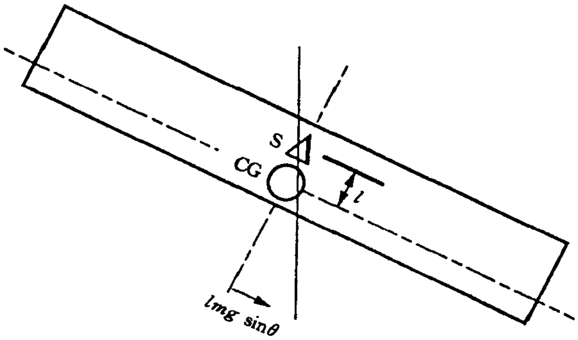

Figure Ph-2 Restoring Moment of a Displaced Mobile Member

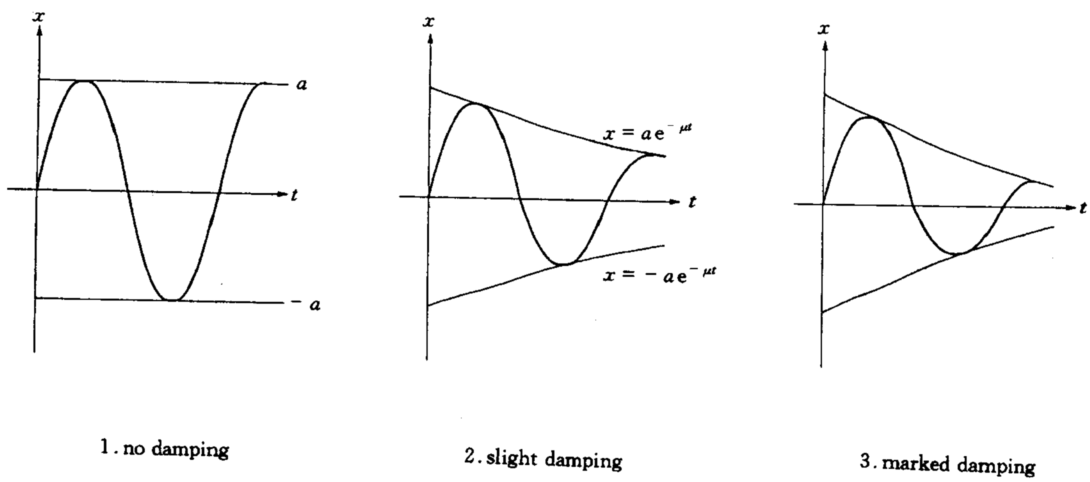

Figure Ph-3 Damping of Swinging Motion of a Single Mobile Member

CG, that is, the larger is the distance l, then the greater is this restoring torque. If, therefore, it is desired for the displaced member to return quickly to its original stable position, then a large value of l should be chosen. On the other hand, if the displaced member is desired to drift slowly to its original position, then l should be small, that is, S should be only slightly above CG.

由此可见，如果设计中欲使迅速复原，应采用较大的 l 值。相反，如果要求缓慢地恢复运动，那该采用小的 l 值，也即是说， S 点该紧靠 CG 点之上。

In practice, the restoring action is in general slowed down dynamically by air resistance against the moving member, in what is known as damping, and yet it could be augmented by any external force which may be wind-driven in origin. This is shown in the following equation of motion for the swinging member:

实际上，恢复运动经常受到空气阻力所引起的阻尼；同时，空气阻力也可加速恢复运动。这种作用可用下列运动公式表达：

$$\underbrace{\frac{d^2x}{dt^2}}_{\text{acceleration 加速}} = \underbrace{-2\mu\frac{dx}{dt}}_{\text{damping 阻尼}} \underbrace{- \omega^2 x}_{\text{gravity 重力}} + \underbrace{P\sin(pt)}_{\text{external 外力}}$$

In the above equation, x denotes displacement and t time. The general solution of this differential equation is

上式中 x 为位移， t 为时间。这一常微分方程的通解为

$$x = \underbrace{\frac{P}{\sqrt{[(\omega^2 - p^2)^2 + (2\mu p)^2]}}\sin(pt - \eta)}_{\text{forced 强制}} + \underbrace{a\exp(-\mu t)\sin(\omega t + \epsilon)}_{\text{intrinsic 内禀}}$$

Figure Ph-3 shows the effect of damping through air resistance on the periodic swinging motion of a single member. In Figure Ph-3.1, the motion is not damped at all, that is $\mu = 0$, and the amplitude of the swinging motion is seen to remain constant at the value a. Figure Ph-3.2 shows slight damping with a progressive decrease in the amplitude of swing diminishing with time as $x = a\exp(-\mu t)$, while in Figure Ph-3.3, damping progresses much

图 Ph-3 表示了空气阻力对一个摆动组件的阻尼作用。图 Ph-3.1 表示运动未受阻尼，即 $\mu = 0$, 摆动幅度始终维持常数 a 值。图 Ph-3.2 表示阻尼较小时，摆动幅度随时间按 $x = a\,e^{-\mu t}$ 缓慢缩小。图 Ph-3.3 则表示阻尼较大时的情况。阻尼常数 μ 取决于一系列的因素，包括组件的表面积。

faster when the value of μ is higher. The damping constant is dependent, among other factors, on the surface area of the member.

Figure Ph-4 shows the effect of the frequency of the external force on swinging. It can be seen from the figure that as the frequency p of the external force approaches the intrinsic frequency ω of the system, the amplitude A of the swinging member increases to a maximum at $p = \omega$. The amount of this increase is governed by the damping constant μ, the higher the value of μ the less pronounced is this augmentation. Although it is important to understand what effect the frequency of the external force has upon the amplitude of swinging, the external force in mobile-making is rarely periodic.

图 Ph-4 表示周期性外力对组件摆动的作用。由图可见，当外力频率 p 向组件的内禀频率 ω 渐近时，组件的摆动幅度 A 渐向最大值。摆动幅度的增长在很大程度上取决于阻尼常数 μ，μ 值越大，增长越小。虽然从力学上讲，我们需了解外力频率对摆动幅度的影响，但对制作几何动艺，外力一般并非具有周期性。

It is evident also that the motivating force for setting a mobile train in motion is generally aerodynamic and thus shares the same nature as damping. Thus the contradiction arises that easy initiation of motion is often accompanied by effective damping. It therefore remains for the ingenuity of the mobile designer as to the proper choice of some optimal value of μ for his mobile to execute the motion he has in mind.

可以明显地看出：推动动艺的外力属气动，它无异于阻尼它运动的外力。由此可看到一种矛盾：易动亦易阻。几何动艺的设计，也要求如何选择最佳 μ 值的条件，使其实现设计者所期望的运动。

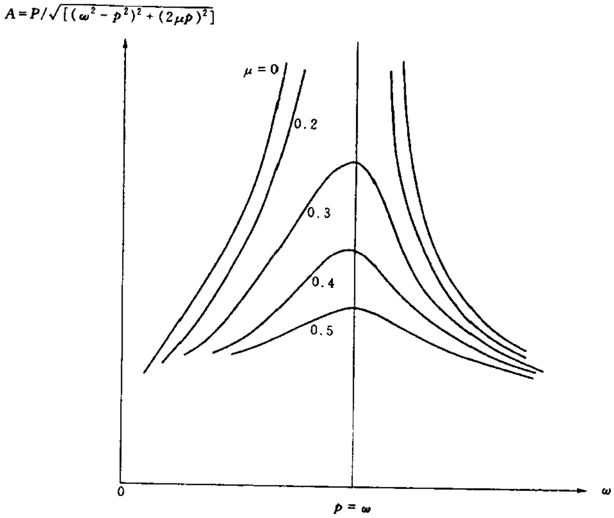

Figure Ph-4 Effect of Frequency of External Force on Swinging

DESIGN TECHNIQUE

设计

Making mobiles consists first of all the conceptualization and design of forms in motion. The forms we are dealing with are inanimate and geometric, and their motion spatial and random for each individual member of a mobile train, yet coordinated with respect to one another. The geometric forms are easily definable — lines, triangles, rectangles (including squares and their deformed kin, the rhomb) and circles (including rings and sectors). The assemblage of mobile members is generally mathematically ordered with respect to length, size and/or shape, to form a train, which is designed to possess certain characteristic motion in space. This mathematical ordering has its root in aesthetics but must be subject to the law of statics in balancing the members. Figure D-1 illustrates certain concepts of this mathematical ordering of mobile members: identical, log-sized, shape-ordered, etc.

Geometric mobiles define a realm of abstract art in motion, directed to concept in space and motion, and is therefore not supposed to imitate objects belonging to other realms of existence, for instance, animals. This applies particularly to the naming of mobiles. Mathematical analysis employed in designing mobiles is expected to yield simple analytic formulations for easy computation. Rendition of the concept and design of forms in motion, calls for craftsmanship in the fabrication of mobiles with precision and care in following as closely as possible computed results.

制作几何动艺首先要形成形状和运动的构思。几何动艺组件的形状非取自生命界，而系几何上可述 — 线、三角形、四边形 (包括方形和菱形) 和圆 (包括环和扇形) 。组件于空间的运动属各自无规，但又相互影响。几何动艺的组件一般在长度、尺寸、形状等方面有一定的关系：相同、相似或成比例。组合后，几何动艺必须能实现某种特征的运动。这种数学组合既源于美学但又必须服从组件的力学平衡。图 D-1 表示了一些数学组合的例子：等同、对数增大、逐级变形等。

几何动艺既源于抽象形状在空间运动的构思，因此并不模仿动、植物。几何动艺的命名也同样着重运动的方式。数学模拟旨在推导出简明的解析解，便于设计时的演算。实现构思、设计和模拟于作品中，要求精细的手工以及准确无误地体现智力创作。

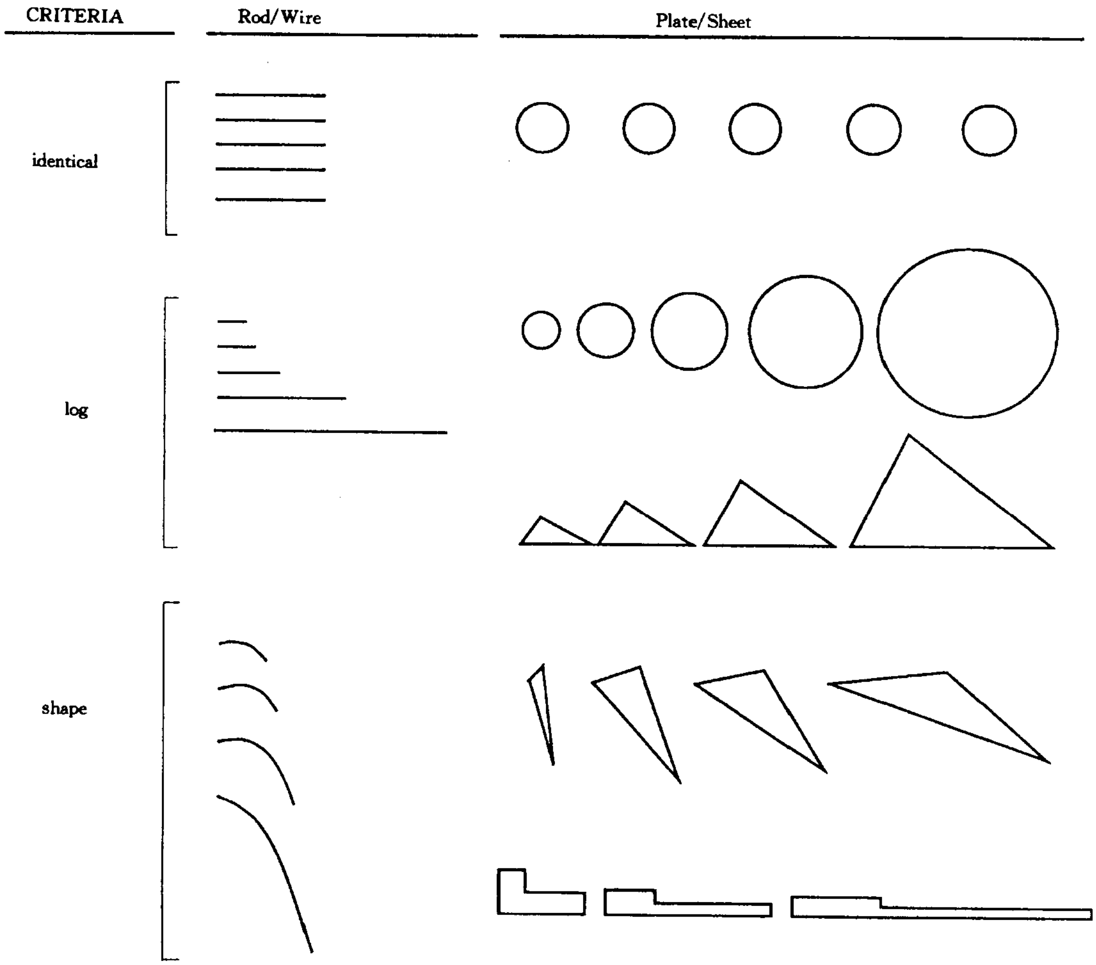

Figure D-1 Mathematical Ordering of Mobile Members

Layout/Stringup

First of all, the geometric shapes need to be cut from some parent material, which, for the present book, will be limited to rod and wire as one category and plate and sheet as the other. Cutting these geometric shapes will be referred to as "**layout**," and the layout scheme will be subject to the jigsaw constraint already mentioned. One aspect of excellence in mobile layout is not only the maximal utilization of material, but the capability of re-assembling the cut members to form a geometrically definable parent geometric shape. Some examples of layout of mobile members are given in Figure D-2:

ROD/WIRE:

equal lengths; lengths ordered to certain mathematical formulation; curves; S-bends; 4-sided bends

PLATE/SHEET:

Triangles: from a parent triangle (equilateral or otherwise); from a rectangle (having different length-to-breadth ratios)

Rectangles: rectangles from a parent rectangle; squares from a parent square; "L's" from a parent square or a parent rectangle

Circles: disks from the quadrants of a square; rings (concentric or eccentric, up to the extreme of sharing a common point of tangency); sectors from part of a disk (concentric or eccentric); disk together with its non-centric sector cutouts

In order to minimize waste, the size of a mobile is preferably tailored to the dimension of the *available* material. For that purpose, all

下料和联结

几何动艺的组件首先须从原材料上切割下来，这些原材料在本书中将限于棒或丝、板或片。下料将循“七巧板”不浪费原料的原则，已如前述。一个合格的几何动艺要求充分利用原材料，并能将组件拼回具有简单可述几何形状的原件。图 D-2 将进一步说明这种下料的思想。

棒 / 丝： 等长；按某种数学规律更变长度；曲线簇；折线簇；方旋簇

板 / 片：

三角形： 切自一个原始三角形 (等边的或其它)；
切自一个矩形 (不同长宽比)

矩形： 切自一个原始矩形；
正方形切自一个原始正方形；
从一个矩形或正方形切下 L 形组件

圆： 四个圆盘切自一个正方形的四个象限；
环 (同心或偏心)；
扇形 (同心或偏心)；
圆盘及其偏心的扇形

为了节约材料，几何动艺一般按现有材料的尺寸确定大小后再下料。为了达到这一目的，本书中所有数学推导所得尺寸都属无量纲，一般基于某一边长。