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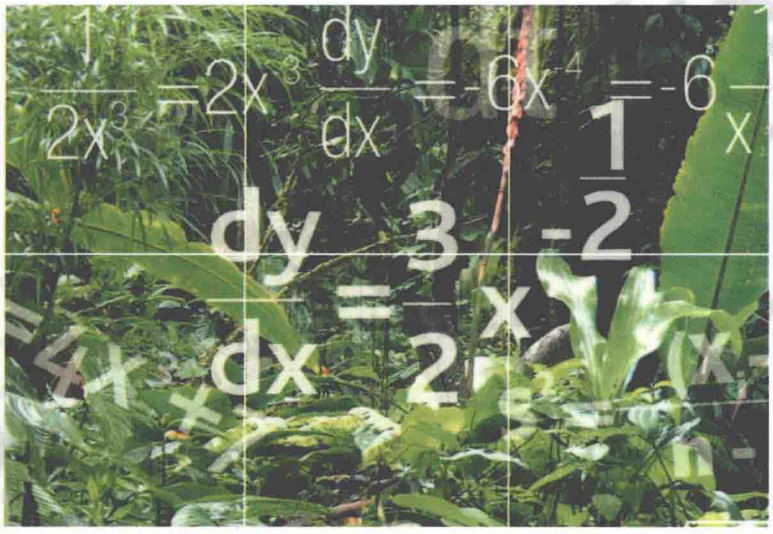

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Instant Notes

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精要速览系列
Instant Notes in

Mathematics and Statistics for Life Scientists

生命科学中的数学与统计学

（导读版）

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内 容 简 介

“精要速览系列(Instant Notes Series)”丛书是国外教材“Best Seller”榜的上榜教材。该系列结构新颖,视角独特;重点明确,脉络分明;图表简明清晰;英文自然易懂,被国内多所重点院校选用作为双语教材。

全书包括 11 章,分别是数字在生命科学中的应用、度量与单位、资料处理与表示方法、数学基础知识、数学应用、变化率:微分、变化率:积分、方程、方程应用、统计学基础知识、统计检验方法的选择。

本书适合普通高等院校生命科学、医学、农学等相关专业使用,也可作为双语教学参考教材使用。

Aulay Mackenzie
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A1 USING NUMBERS IN THE LIFE SCIENCES

Key Notes

Quantification The interpretation of data, diagnosis, analysis and deductions in scientific study cannot be made without measurements of some type.

Mathematics The relationships between quantities, magnitudes and forms are dealt with in mathematics.

Statistics The detection of patterns in data sets is facilitated by statistics.

Biological data The vast diversity in biological systems causes the data to be 'noisy'. Therefore detecting patters requires rigorous analysis.

Quantification

Mathematics and statistics are important in the life sciences because scientific study of any type depends on **quantification**. It is rarely possible to be able to make any interpretation, diagnosis, analysis or deduction without measurements or counts or some kind. So, whilst your main interest may be immunology or coral reef ecology, nutrition or biotechnology, you need to have a grasp of the basic tools to handle numbers. This book aims to give you a basic toolkit in an accessible and digestible format to help your forays into your chosen field.

Mathematics

The group of related sciences which includes algebra, geometry and calculus is known as **mathematics**. The inter-relationships between numbers, quantities, shapes and space are studied by using special notation.

Statistics

The detection of patterns in large data sets, such as frequently encountered in the life sciences, is facilitated by **statistics**, which is a branch of mathematics rather than a separate discipline. Crudely, the role of general mathematics can be described as 'taming' the numerical patterns in data, while statistics interprets the patterns.

Biological data

Biological systems differ from some other sciences, such as engineering and physics, in that the genetic variation between individual organisms, and between populations and species creates a vast diversity in responses and patterns. This means that **biological data** has a tendency to be 'noisy'. This is particularly true in ecological studies, where multiple biological and other environmental factors may be impacting upon the data set. For this reason, rigorously detecting patterns in biological data requires particularly careful analysis, and indeed the field of statistics has partly grown out of the analysis required for biological applications.

The topics in this book cover the basic needs of a life science undergraduate,

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but the book is not intended to be comprehensive. I have tried to avoid coverage of topics or levels of detail that are not wholly necessary: nothing is here on the basis that it will 'do you good', but there will be some areas and some students which require more advanced coverage than this.

I have adopted two somewhat different approaches to the mathematical and statistical components. For the mathematics, it is important to understand what the procedures do and how they work in order to be able to implement them, so there is step-by-step coverage. In contrast, for the statistics, it is important to know what a particular test does, but not to deal with the mathematical underpinnings. A simple '**black box**' approach is taken – that is to say, the inner workings of the mathematical mechanics of the statistical tests are not covered, except where absolutely necessary. The mission is to help you locate the right test, apply it correctly and understand the result. Just as effectively driving a car does not require intimate mechanical knowledge of the engine, so statistical tests can be properly and effectively used without a detailed understanding of what makes them tick. My underlying assumption is that you will use statistical software to perform the calculations, and I do not adhere to the viewpoint that undertaking these by hand would make you better at understanding the test, any more than taking apart a car engine will make you a better driver. If you go on to develop a deeper understanding of statistics, you may find a more mechanistic understanding is useful. Because I assume you will be using software for analysis, there is no appendix of probability tables.

The statistical tests covered are those which are in commonest use and have the broadest application. It may be that you will come across situations that require tests beyond these, but this should not be a common occurrence. In any case, once you have a grasp of the tests described here, you will be well equipped to tackle others. Also, a brief coverage of multivariate methods is included, as much to provide a guide to interpreting these analyses when presented elsewhere as to tackling them yourself.

B1 TYPES OF MEASUREMENT

Key Notes

Methods of measurement
Different approaches to measurement are required in the life sciences. Variables may be continuous or categorical. There are four levels of measurement: nominal, ordinal, interval and ratio scales.

Accuracy and precision
Accuracy is the closeness of a measured value to the true value. Precision is the repeatability of measurement of the same datum.

Errors
An error is the difference between a number and the number it approximates.

Bias
Bias is a measurement error in the data which causes systematic distortion of the measured values in one direction.

Significant figures
The number of significant figures indicates the reliability of a measurement. It conveys numerical meaning, not just magnitude.

Methods of measurement

Applying measurements appropriately in all sciences is a key skill. In the life sciences data comes in a range of forms that require different approaches to measurement. Some variables are **continuous** (or **metric**), which fall along an uninterrupted scale (e.g. length, mass, temperature) whilst count data can only be whole numbers and are **categorical** (also termed **discrete, discontinuous** or **nonmetric**). Four levels of measurement are recognized: the **nominal, ordinal, interval** and **ratio** scales.

A **nominal scale** classifies observations into exclusive categories that have no relative rank. Examples include species, gender, color and habitat type.

An **ordinal scale** classifies observations into ranked exclusive categories. Examples include abundance scales (e.g. the DAFOR scale (**d**ominant, **a**bundant, **f**requent, **o**ccasional, **r**are)) used to record the abundance of plant species in a quadrat) and developmental status (e.g. newborn, juvenile, yearling, adult).

An **interval scale** defines observations on a continuous scale that has no absolute zero. Examples include the Celsius temperature scale and the calendar date. (Note that the absence of an absolute zero means it is not true to say that 15°C is three times warmer than 5°C, nor that birds arriving on the 8th May are twice as late as those arriving on the 4th May.)

A **ratio scale** defines observations on a continuous scale that has an absolute zero. Examples include length, weight and most physical measurements. Thus, in contrast to measurements made in the interval scale, it is true to say that a plant leaf of length 45 mm is half the length of one of 90 mm length.

Accuracy and precision

When measurements are being made, it is necessary that they be accurate or precise or both. Unfortunately, the terms 'accuracy' and 'precision' are often colloquially used interchangeably, but the distinction in scientific use is important. **Accuracy** is the closeness of a measured value to the true value. **Precision** is the repeatability of measurements of the same datum (i.e. the closeness of measured values to one another) (see *Fig. 1*). It is possible for a **bias** in the measurement apparatus to give rise to very precise, repeatable values which were inaccurate.

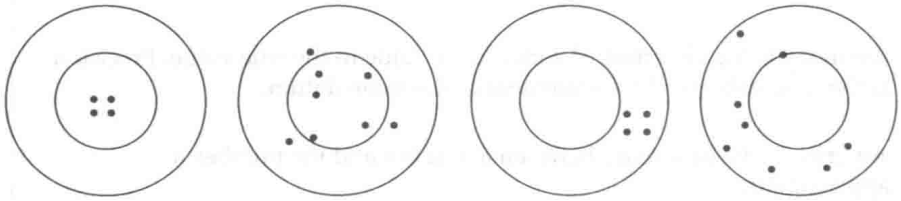

Fig. 1. Target diagrams of precision and accuracy.

Errors

Error is the difference between a number and the number it approximates. It is impossible to remove all error from estimates, but careful scientific procedure can limit it. If we wish to estimate the mean length of a species of bumble bee, we may choose to measure thirty specimens and take the mean value of this sample. Two sources of error would arise: **measurement error**, due to problems with handling and using the measurement equipment, and **sampling error**. Sampling error arises because only a subset of the whole population is being measured. There is a third source of error, **rounding error**, that arises as a result of numbers that have been calculated with imprecise subcomponents or parameters. An example of this is given in the example cited in Topic D3 (see p. 36).

To achieve accurate results, it is important to minimize all sources of error. Measurement error is minimized by using carefully standardized procedures and accurate instruments. Sampling error declines as the sample size increases, so larger samples are always better, but are more costly in terms of time and effort. Sampling procedures and choosing the best compromise in sample size are discussed in Topic K2.

Bias

Bias is a type of **measurement error** in the data which causes **systematic** distortion of the measured values in one direction. Bias can be caused by defective or incorrectly calibrated instruments, by the effects of experimental manipulation or preparation, or by the observer anticipating particular results and interpreting data with this perspective (e.g. by ignoring data points which disagree with this preconception). To minimize the occurrence of bias, carefully standardized procedures should be adopted with well calibrated instruments. In experiments where observer bias may be strong (e.g. in drug trials involving placebos), 'blind' (subjects who are unaware of their treatment regime) or 'double-blind' (both the subjects and observers are unaware of the treatment regime) approaches may be useful. Bias can be detected by measuring a variable in the same set of samples in different ways and checking for consistent results.

Significant figures

It is common for numbers to be calculated which, in their raw state, erroneously appear to indicate very high levels of accuracy. Stating these numbers to a limited number of significant figures reduces the implied accuracy levels to defendable levels. The number of significant figures indicates the reliability of the measurement and is the number of digits in the number which convey numerical meaning, not just magnitude. So, the statement '100 kg to three significant figures' means that the accuracy is stated as being to within 1 kg of 100 kg, whilst '100 kg to two significant figures' means that the true value may lie between 95 kg and 105 kg. Similarly, '0.010 μm to two significant figures' means that the value lies between 0.009 5 μm and 0.010 5 μm.

Example

A compact disc on my desk has a radius of 60 mm, to the nearest millimeter. As the circumference of a circle is given by πr, where the value of the constant, π, is 3.141 592 65 ..., the circumference of the disc is therefore 3.141 592 65 ... × 60 mm, which gives 188.495 559 2 ... mm. As the initial measurement was only accurate to the nearest millimeter, it is clearly nonsensical to state a derived value as having far higher accuracy. As the measurement was taken to two significant figures, so the circumference of the disc should be stated as 190 mm (to three significant figures).

General suggested rules

- Calculations involving measured quantities should be **no more precise** than the **least precise measurement**.
- Means should be stated to a level of accuracy one significant figure greater than that used in the raw data.
- **Standard deviations** should be stated to a level of accuracy two significant figures greater than that used in the raw data.

B2 Units: The Système International

Key Notes

The Système International

The internationally recognized metric system of units, based around the meter, kilogram and second. There are seven base units: length, mass, time, electric current, thermodynamic temperature, amount of substance and luminous intensity. Each has a specific symbol.

Expressing data in the SI

Numerical data needs to be accompanied by appropriate units. In the Système International specific notations and spacings of units are used.

Deviations from the SI

In the life sciences deviations from the SI are common as some other units are easier to use.

The Système International

Having a single unified system of units greatly aids the communication of data and scientific understanding and also simplifies calculations. The **Système International d'Unités**, usually shortened to **SI**, is the internationally recognized metric system, based around the meter, kilogram and second.

The SI system consists of **seven base units** and two supplementary units (*Table 1*); each of these has a specific symbolic abbreviation. These **fundamental units** can be combined to give **compound units**, of which the more commonly used are given special symbols (*Table 2*).

Prefixes denote multiplication factors of 10^3 and are used to make large or small numbers manageable (*Table 3*).

Table 1. The base and supplementary SI units

Measured quantity	Name of SI unit	Symbol	
Base units			
Length	meter	m	
Mass	kilogram	kg	
Amount of substance	mole	mol	
Time	second	s	
Electric current	ampere	A	
Temperature	kelvin	K	(note: NOT °K)
Luminous intensity	candela	cd	
Supplementary units			
Plane angle	radian	rad	
Solid angle	steradian	sr	

Table 2. Some important derived SI units

Measured quantity	Name of unit	Symbol	Definition in base units	Alternative in derived units
Force	newton	N	$m\ kg\ s^{-2}$	$J\ m^{-1}$
Energy	joule	J	$m^2\ kg\ s^{-2}$	N m
Pressure	pascal	Pa	$kg\ m^{-1}\ s^{-2}$	$N\ m^{-2}$
Power	watt	W	$m^2\ kg\ s^{-3}$	$J\ s^{-1}$
Radioactivity	becquerel	Bq	s^{-1}	
Luminous flux	lumen	lm	cd sr	
Illumination	lux	lx	$cd\ sr\ m^{-2}$	$lm\ m^{-2}$
Frequency	hertz	Hz	s^{-1}	
Enzyme activity	katal	kat	$mol\ substrate\ s^{-1}$	
Electric potential difference	volt	V	$m^2\ kg\ A^{-1}\ s^{-3}$	$W\ A^{-1}$
Electric resistance	ohm	Ω	$m^2\ kg\ A^{-2}\ s^{-3}$	$V\ A^{-1}$
Electric conductance	siemens	S	$s^3\ A^2\ kg^{-1}\ m^{-2}$	$A\ V^{-1}$ or Ω^{-1}

Table 3. Prefixes used in the SI

Multiple	Prefix	Symbol
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E

Expressing data in the SI

When data are expressed using the SI it always needs to be accompanied by the appropriate units (except in unusual cases such as pH and dimensionless ratios).

The SI incorporates a particular spacing and use of symbols. For example, a measurement of 302 cm (to the nearest centimeter) should be expressed as 3.02 m. Note that

- there is a space between the number and the units,
- there is no full stop to indicate abbreviation,
- units are always in singular form.

Thus 3.02m, 3.02 m. and 3.02 ms are all incorrect.

In the case of **compound units**, for example if the velocity of a moving animal was recorded as 1.56 meters per second, this is correctly expressed as $1.56\ m\ s^{-1}$. Note that

- there is a space between the separate symbols,
- that a negative power is used, not a solidus (/).

Thus $1.56\ ms^{-1}$ and 1.56 m/s are both incorrect.

In the SI, **prefixes** should be used to denote multiples of 10^3 so the numbers

are always kept between 0.1 and 1 000. Thus a measurement of 6 241 m should be expressed as 6.241 km. Note that there is no space between the prefix and the unit symbol.

Deviations from the SI

In the life sciences deviations from the SI are common: previously used, or more convenient, units for volume, concentration, temperature, time and light are encountered frequently.

Strictly the SI unit of **volume** is the cubic meter, m^3. However, use of the liter (l or L) and milliliter (ml or mL) is still widespread in many laboratory applications. In calculations it may be most convenient to convert liters to SI units: 1 liter = 1×10^{-3} m^3.

Details concerning **concentration** are dealt with extensively in Topic B3.

The SI unit of **temperature** is the **kelvin** (K) but this is rarely used in everyday life science applications where the **Celsius** scale (°C) is employed. This scale has interval steps of the same magnitude (i.e. a 1 K increase in temperature is exactly the same as 1°C increase), but the zero point is at 275.15 K, the melting point of pure ice at standard pressure. (Standard temperature and pressure (STP) are 293.15 K and 0.101 325 MPa, respectively.)

In SI the base unit for **time** is the **second** (s), and this should be used where possible. Nevertheless, longer time scales may be better such as hours (h), days (d) and years (yr) may be more appropriate in some situations.

The SI base unit for luminous intensity (**light**), is the candela (cd) and the derived units the lumen and lux. These are rather substandard compared to the high precision possessed by the other base units. These units are derived from the response to light of the human eye (from a small sample of 52 US soldiers in 1923). As light sources differ in their spectral qualities and biological receptors (e.g. eyes, skin, plant chloroplasts) differ in their spectral sensitivities, the candela has rather limited value in studies not primarily concerned with human vision. Therefore it is preferable to express light either in terms of energy content (e.g. W m^{-2}) or photon density (e.g. μmol m^{-2} s^{-1}), and it is often valuable to specify the spectrum involved.

It may be necessary to convert between non-SI and SI units, for example to allow comparison with results in the older literature. *Table 4* gives a range of conversion factors.

To convert from non-SI to SI, multiply the number in the old units by the conversion factor.

Example

To convert square inches to square meters:

$$1\,452\ \text{in}^2 = 1\,452 \times (645.16 \times 10^{-6}) = 0.936\,77\ \text{m}^2$$

To convert a number in SI units to the non-SI form, multiply by the reciprocal.

Example

To convert kilograms to ounces:

$$2.314\ \text{kg} = 2.314 \times 35.274\,0 = 81.624\,0\ \text{oz.}$$

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