INSTRUMENTATION AND MEASUREMENT IN ELECTRICAL ENGINEERING

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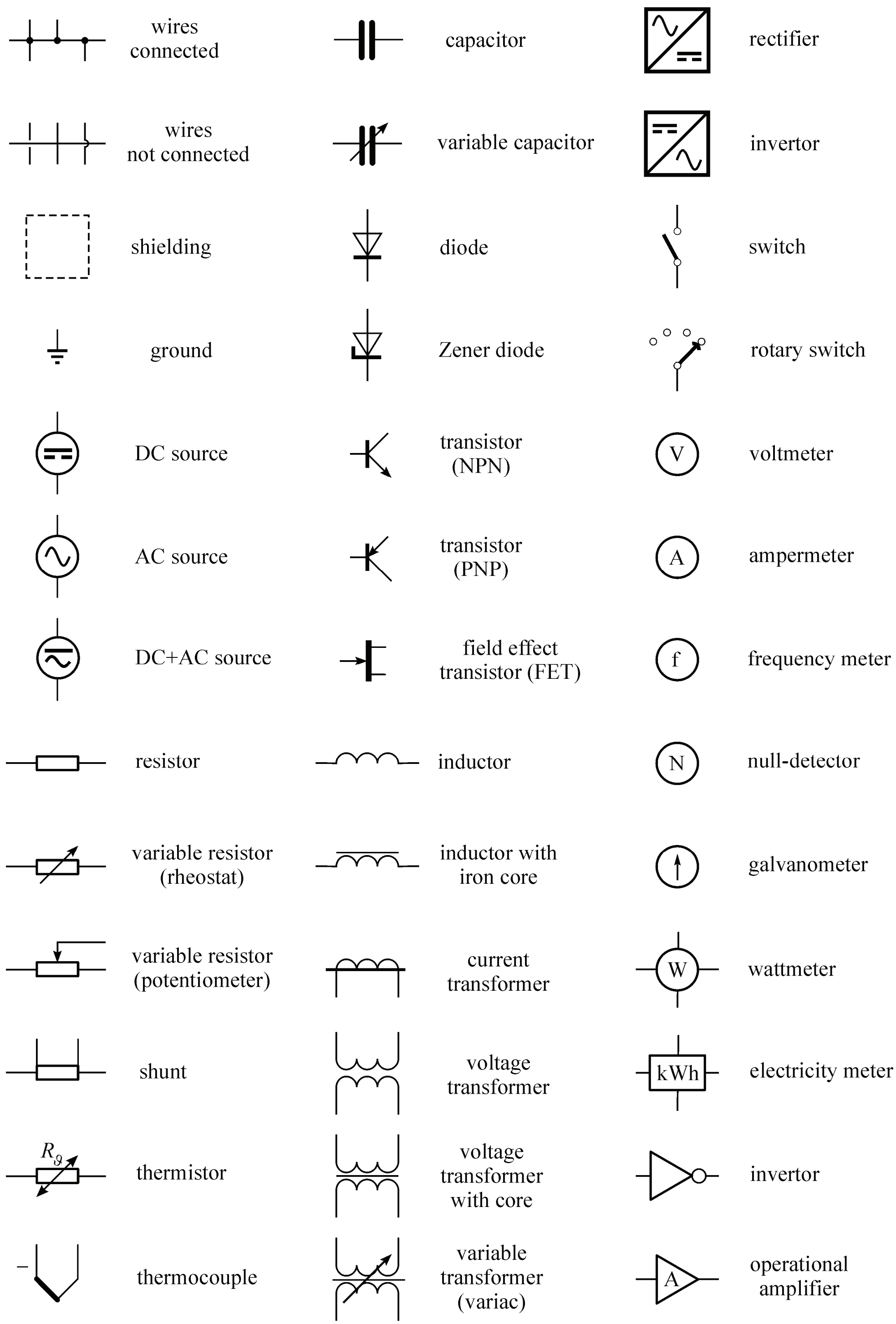
Some of the electrical symbols used in this book



PREFACE

The inclusion of an electrical measurement course in the undergraduate curriculum of electrical engineering is important in forming the technical and scientific knowledge of future electrical engineers. This book explains the basic measurement techniques, instruments, and methods used in everyday practice. It covers in detail both analogue and digital instruments, measurements errors and uncertainty, instrument transformers, bridges, amplifiers, oscilloscopes, data acquisition, sensors, instrument controls and measurement systems. The reader will learn how to apply the most appropriate measurement method and instrument for a particular application, and how to assemble the measurement system from physical quantity to the digital data in a computer. The book is primarily intended to cover all necessary topics of instrumentation and measurement for students of electrical engineering, but can also serve as a reference for engineers and practitioners to expand or refresh their knowledge in this field.

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INTRODUCTION

Measurement followed man from the very beginning of its development. Measuring methods and measuring instruments were developed in parallel with the development of electrical engineering. However, some physical laws were derived based on measurement results, such as the Biot-Savart law, when in 1820, the French scientists Jean-Baptiste Biot and Félix Savart established the relationship between an electric current and the magnetic field it produces. Although science and metrology (the science of measurements) are developing quickly, one should always remember that a measurement principle established more than 150 years ago can still be applicable today. There will be many such principles explained in this book. As the instrumentation becomes more advanced, results will only become more precise.

The basic purpose of metrology is best described by the famous Italian scientist Galileo Galilei: "Measure everything that can be measured and try to make measurable what is not yet measurable." The term *metrology* is derived from the Greek words *metron*–to measure–and *logos*– science. The process of measurement involves comparison of the measured quantity with the specific unit; it is therefore necessary to know the unit of measurement with the highest possible accuracy. The first modern metrology institute was established in 1887 in Germany. This institute was partly responsible for the sudden rise of strength of German industry in the world. Very soon thereafter, other industrial countries established metrology institutes in order to maintain their places at the top of world industry. With the progress of science foundation around the world, metrology slowly relied more and more on natural phenomena and not on prototypes, as in the past. Today, the only unit of measurement embodied in prototype–kilogram–is stored in Sèvres near Paris, but in recent years, the metrology world appears to desire to define this unit by natural phenomena just like all the others.

Today, metrology is based on natural laws and is unique in how the units can be realized anywhere in the world, if only one has the necessary knowledge and equipment. The foundation of today's metrology is the International System of Units (SI), adopted in 1960. This system consists of seven base units and a large number of derived units, 23 of which have their own special names and signs. Only electrical current is included in the seven base units from electrical engineering. All others, such as units for electrical resistance and voltage, are derived units.

Chapter 1 gives an overview of the modern SI system of units, and explains the definition of SI base units, its realization, and its standards.
Chapter 2 describes measurement errors, calculation of measurement uncertainty, and instrumentation limits of errors.
Chapter 3 describes the different measuring elements such as resistors, inductors, and capacitors, as well as voltage standards.
Chapter 4 describes the analogue measuring instruments, and how to use different types to measure various AC and DC voltages and currents.
Chapter 5 is about the compensation measurement methods, such as bridges and compensators. AC and DC calibrators are also described.

Chapter 6 gives an overview of instrument transformers, their uses, and testing methods for determination of phase and current/voltage errors.
Chapter 7 describes the use of operation amplifiers in measurement technology, and how to use them to build electronic instruments and other devices using the op-amps.
Chapter 8 gives an overview of cathode ray tube and digital storage oscilloscopes. How to use oscilloscopes to measure different electrical quantities is also described.
Chapter 9 describes the construction and use of digital multimeters, and provides an overview of different analogue to digital converters used in various digital instruments.
Chapter 10 describes measurement methods to measure different electrical quantities, such as voltage, current, resistance capacitance, and many others.
Chapter 11 describes the historical development of instrument control with the use of the personal computer, as well as different connectivity interface buses and software support for both stand-alone and modular instrumentation.
Chapter 12 gives an overview of the measurement system, and describes the most popular sensors, signal conditioning, and data acquisition hardware.

TABLE OF CONTENTS

Acronyms and Abbreviations

A/D	analogue to digital converter
AC	alternate current
ADC	analogue to digital converter
API	Application Programming Interfaces
BIPM	International Bureau of Weights and Measures
CGPM	General Conference on Weights and Measures
CIPM	International Committee for Weights and Measures
CMRR	common-mode rejection ratio
CMV	common-mode voltage
CPU	central processing unit
DAQ	digital acquisition
DC	direct current
DMM	digital multimeter
DSO	digital storage oscilloscope
DVD	cgital video disk
DVM	digital voltmeter
EA	European cooperation for Accreditation
EMF	electromagnetic force
FER	Faculty of Electrical Engineering and Computing in Zagreb
FFT	Fast Fourier Transform
GND	ground
GPIB	General Purpose Interface Bus
HPIB	Hewlett Packard Interface Bus
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IICP	Industrial instrumentation control protocol
IMCPM	instrument with moving coil and permanent magnet
ISO	International organization for standardization
JAVS	Josephson Voltage Array standard
LabVIEW	Laboratory virtual instrumentation engineering workbench
LAN	Local Area Network
LCD	Liquid crystal display
LVDT	Linear Voltage Differential Transformer
LXI	LAN Extensions for Instrumentation
MEMS	Micro Machined Inertial Sensors
MOSFET	metal–oxide–semiconductor field-effect transistor
NMI	National Metrology Institute
NRSE	Non-referenced single ended
OP-AMP	operational amplifier
PCI	Peripheral Component Interconnect
PEL	Primary Electromagnetic Laboratory
PTB	Physikalisch Technische Bundesanstalt
PTR	Physikalisch Technische Reichsanstalt
PWMDAC	analogue to digital converter with pulse width modulation
PXI	PCI eXtensions for Instrumentation

RMS	root mean square
RS-232	Recommended Standard 232
RSE	referenced single ended
RTD	Resistance Thermal Devices
SCPI	Standard Commands for Programmable Instruments
SI	Le Système International d'Unités
SoC	System on chip
USB	Universal Serial Bus
USBTMC	USB Test& Measurement Class
VISA	Virtual Instrument Software Architecture
VME	Versa Module Eurocard
VXI	VMEbus eXtensions for Instrumentation
WSN	wireless sensor networks

1. INTERNATIONAL SYSTEM OF UNITS - SI

The International System of Units (SI - Le Système International d'Unités) was established in 1960. It was an important step, after decades of hard work, to overcome the many different units used throughout the world. The need for a unified system of units was evident after the Industrial Revolution in the 18th century. Several important events also contributed to and sped up the process, especially the World Fairs in London (1851) and Paris (1876).

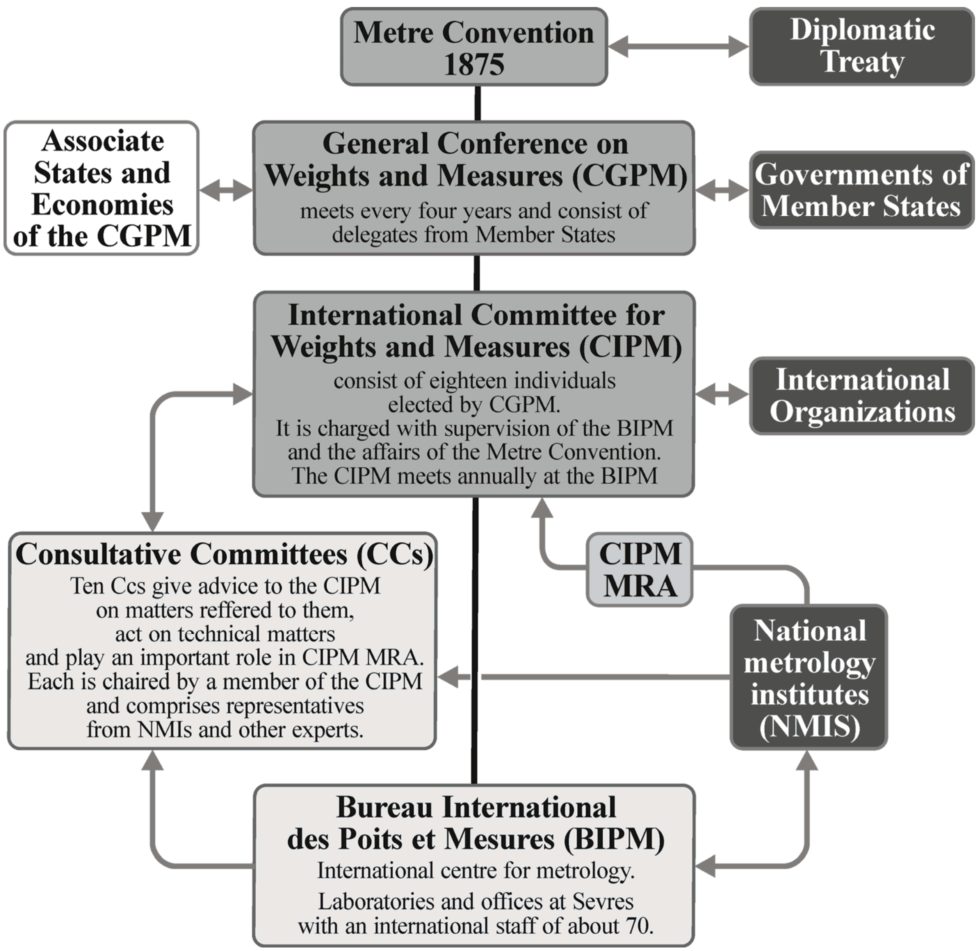

Figure 1.1 Relationships between different metrology organizations in the world

The origin of today's SI system of units goes back to May 20^{th}, 1875, when the representatives of the 17 most technologically-advanced countries of the world signed the Treaty of the Metre (also known as the Metre Convention). At that time three important organizations were created, with the task to take care of the metric standards. These institutions, which are still working today, are:

- International Bureau of Weights and Measures (**BIPM**);
- General Conference on Weights and Measures (**CGPM**);
- International Committee for Weights and Measures (**CIPM**).

The International Committee for Weights and Measures (CIPM) works through ten consultative committees that provide recommendations to the General Conference on Weights and Measures (CGPM), which decides on the resolutions at least once every 6 years. These resolutions are obligatory to the signatories of the Metre Convention (52 countries signed the treaty by the end of 2009). The International Bureau of Weights and Measures (BIPM) is the scientific institute governed by the CIPM. Its role is storing and realizing international primary units, improving measurement methods and units, and comparing different standards for member countries (Figure 1.1).

The SI system of units is a modern metric system, which is used throughout the world today. Even in countries where units that do not belong to SI are used, like in the USA, units are also derived from SI units. It can be stated that the International System of Units (SI) is coherent, unified, and uniform. It is coherent because it is composed of seven base units (meter, kilogram, second, ampere, kelvin, mole, and candela), mutually independent, and units are derived from base units. Coherence means that the basic unit of natural laws is always associated with factor 1 (1x1 = 1, 1/1 = 1; Figure 1.1). It is unified because, except for weight, all units are defined by unchangeable natural constants. It is uniform because the measurements in the dynamics, electrodynamics, and thermodynamics can be compared with each other in terms of conservation of mass and energy (Figure 1.1). The importance of using the SI units is best demonstrated in the unfortunate loss of the **Mars Climate Orbiter** in 1998. The thrusters on the spacecraft, which were intended to control its rate of rotation, were controlled by software that used the unit of **pound force** to make calculations (this is a standard unit for **force** in the United States customary units system). The ratio of SI unit of force **Newton** and the unit of **pound force** is 4.45, and as the spacecraft expected the figures to be in Newtons, the unfortunate mix of units caused the spacecraft to drift into low orbit and be destroyed by atmospheric friction.

1.1 DEFINITIONS OF THE SI BASE UNITS

There is a difference between the unit definition and its realization. The International System of Units (SI) is a set of **definitions**. National Metrology Institutions (NMIs) perform experiments to produce (**realize**) the unit according to the definition, and with some of these experiments the unit can be **stored** in **standards**. The standards are physical objects whose characteristics agree with the **definition** of unit. For example, the unit for **time** is second, and it is defined as the duration of a certain number of periods of the radiation of the atom of cesium-133. Anyone who has the money, knowledge, and equipment can make an atomic clock that produces radiation as defined by the SI unit of second. It is important to emphasize that the atomic clock is not the realization of a second. The realization of a second is the radiation produced by atomic clocks.

There are seven **SI base units** and their **definitions** are:

Unit of length – **meter**: "The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second."

Unit of mass – **kilogram**: “The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.”

Unit of time – **second**: “The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.”

Unit of electric current – **ampere**: “The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10-7 newton per meter of length.”

Unit of thermodynamic temperature – **kelvin**: “The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.”

Unit of amount of substance – **mole**: “The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is ‘mol.’” When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

Unit of luminous intensity – **candela**: “The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.”

There are a few dozen **derived** units, some of which are **named** (e.g., **Ohm**, **Volt**), while the majority has **no special name** (e.g. unit for speed is **m/s**).

As already stated, all derived units must be able to be expressed in terms of base units. This will be explained by the derived unit of electrical resistance **Ohm**, named after the German physicist **Georg Simon Ohm** (1787-1854). The unit symbol is **Ω** (capital Greek letter omega -Ω). Ohm is defined as:

$$\Omega = \frac{V}{A}, \tag{1.1}$$

where **V=W/A**; V is the SI unit of **voltage**, **A** (**ampere**) is the SI base unit for **current**, and **W (watt)** is the SI unit of **force**. As unit **Watt** is derived from SI units **joule** and **newton**, and those units are derived from base SI units **kilogram**, **meter**, and **second**, the Ohm, expressed by the base units of SI, is:

$$\Omega = \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^3 \cdot \mathrm{A}^2 \tag{1.2}$$

This is valid for all derived units, which can be seen in Figure 1.2.

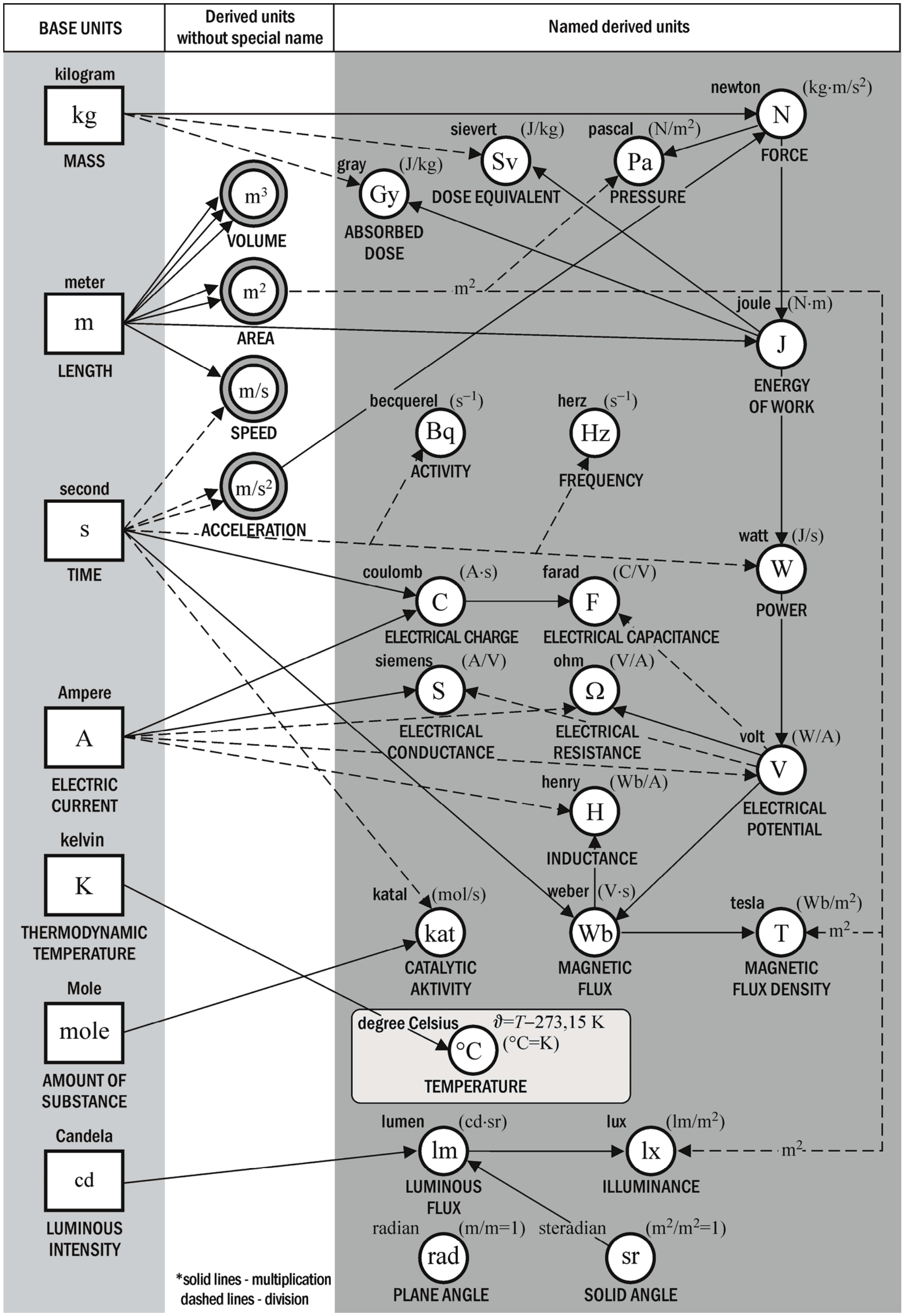

Figure 1.2 SI system – the relationship of base and derived units

1.2 REALIZATION OF UNITS

An example of unit realization is the absolute determination of resistance by the **Thompson-Lampard** calculable capacitance standard. **Calculable standards** are standards whose values can be determined accurately using known dimensions. Such standards should have a simple geometric shape that allows mathematical calculation of standards. This was achieved for the capacitance standard, which was developed by **A.M. Thompson** on theoretical considerations from **D.G. Lampard** in 1956. These considerations show that in the symmetrical arrangement of cylinders A, B, C, and D, according to Figure 1.3, the capacitance between cylinders A and C or B and D is:

$$C_{AC} = C_{BD} = \frac{\varepsilon_0}{\pi}(l_1 - l_2)\ln 2 \qquad [1.3]$$

where ε_0 is the permittivity of vacuum, which can be determined with relative measurement uncertainty of 8x10^9. It is only needed to achieve superb accuracy in measuring the distance between the electrodes, which can be achieved by interference methods, so the total measurement errors of the measurement procedure do not exceed 1x10^7, while the edge effects are avoided by making two measurements at different intervals (l_1 - l_2). This realized SI unit of **farad** has become the starting place for the realization of the SI unit of resistance. Realization of the SI unit of resistance from the realized unit of capacitance is shown in Figure 1.4. This entire sequence of ohm realization is achieved with the measurement uncertainty of about 0.1 ppm.

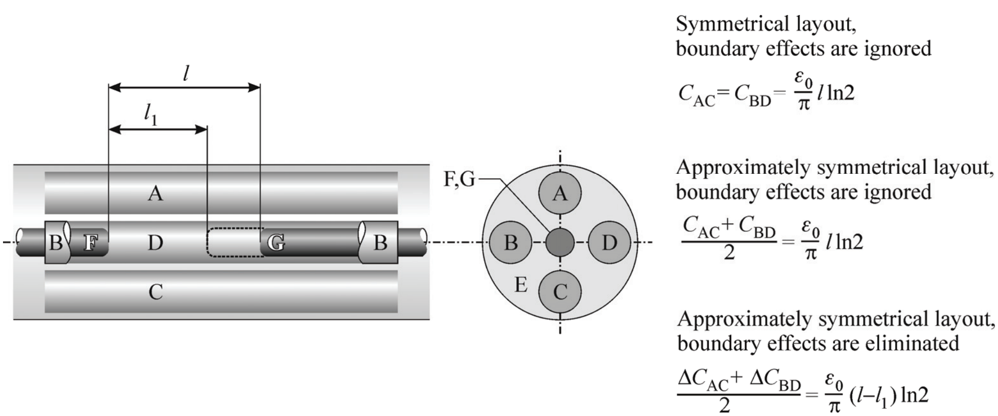

Figure 1.3 Thompson-Lampard calculable cross capacitor

The unit of volt, for example, is the SI unit defined as the power of one watt divided by the current of one ampere. An example of realization of the unit of volt is the voltage balance, which tries to equal the voltage electrostatic force and mass of the known weight. Results thus obtained are assigned to the standards of cheaper and simpler systems such as **Weston cells** and **Zener voltage standard**, or expensive and complicated devices such as the **Josephson voltage source**, as these devices store and do not realize the SI unit of **volt**, because the way they are used does not include continuous comparison of electrical and mechanical power realized in the system of units SI. Such equipment or devices, primary or secondary, are called **standards**.