

Reproducibility: the cornerstone of modern science

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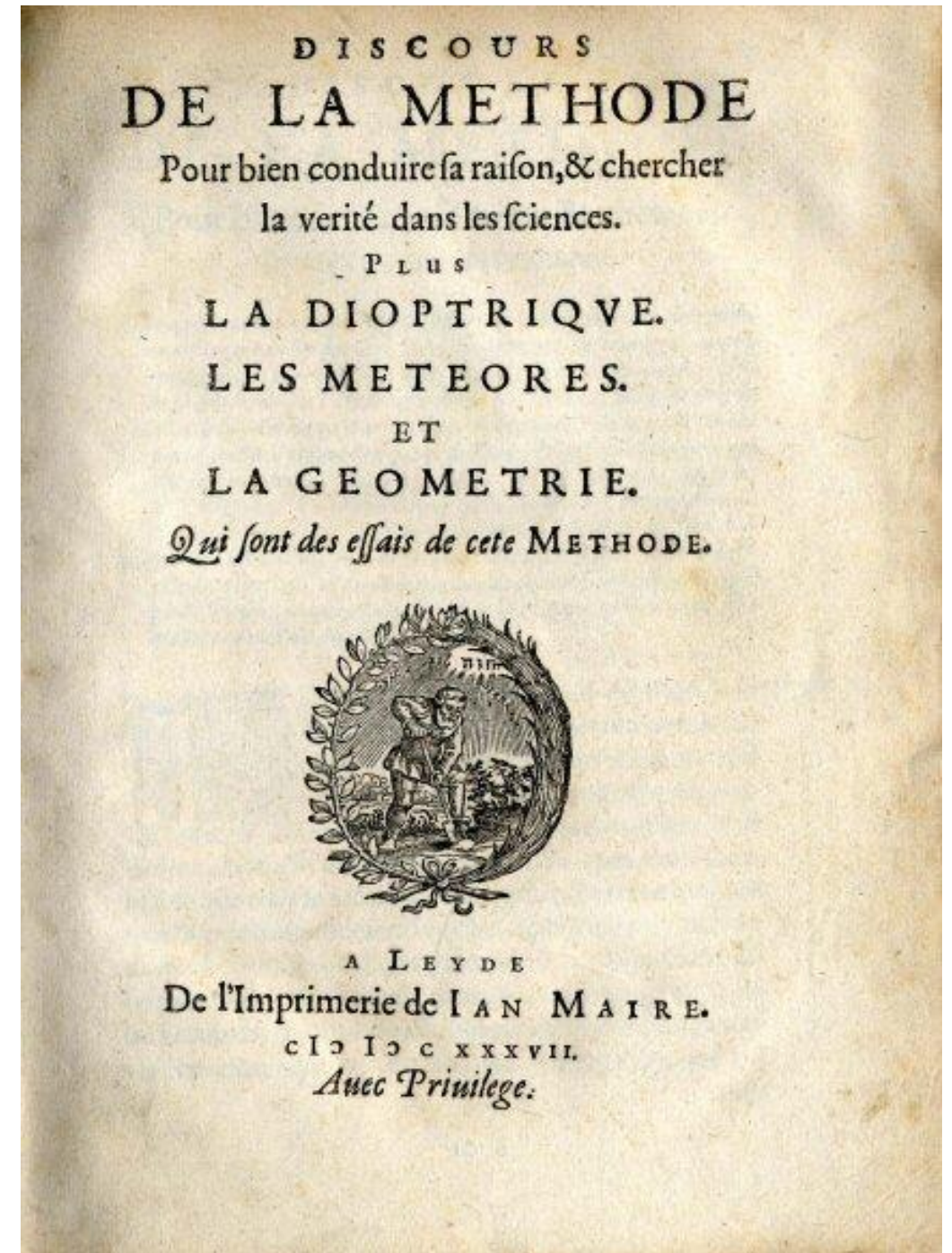
[Developing the
Science of Networks]

The universe can be understood!



Rene Descartes

1649-1700



Descartes: the father of the scientific method

- Key idea: applying the reasoning of mathematics to the laws of nature
 - In math: **Axioms** => **mathematical proof** => **Theorem**
 - In physics: **Observations** => **chain of “foolproof” reasoning** => **Physical law**
- Scientific method = cornerstone of empirical sciences
- **Observations** ~ quantitative and accurate measurements
 - Measurements of the speed of falling objects
 - Measurements of the orbits of planets
 - Measurements of the speed of light

Metrology: the science of measurements

- **VIM 2.2** “metrology: science of measurement and its application

Note: Metrology includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application.”

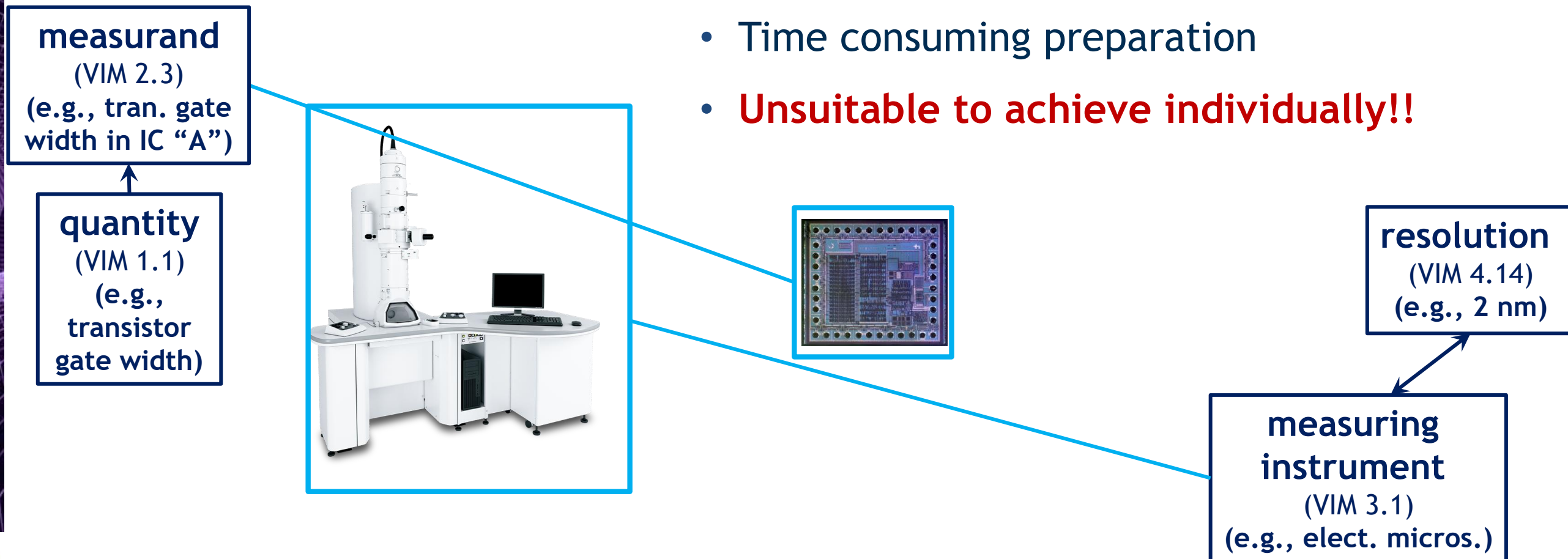


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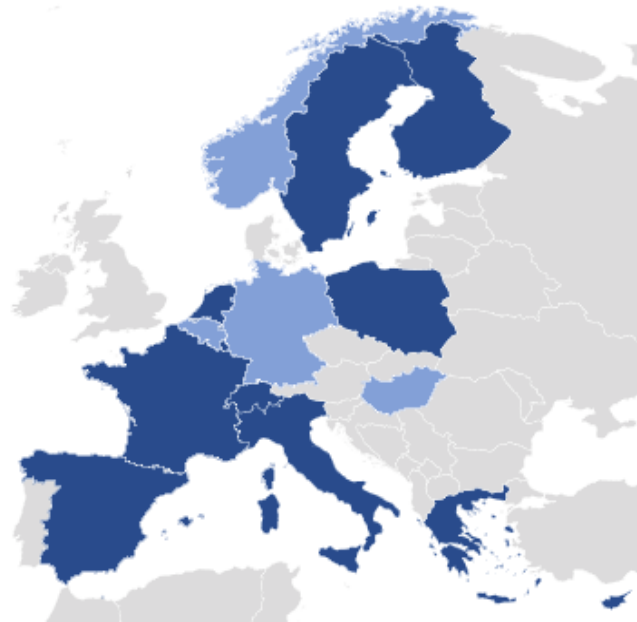
- JCGM 200:2012, “International Vocabulary for Metrology (IVM-**VIM**) - Basic and general concepts and associated terms”, 3rd edition, 2012, Joint Committee for Guides in Metrology (JCGM).
- JCGM 100:2008, “Guide to the expression of uncertainty in measurement (**GUM**)”, 1st edition, 2008, Joint Committee for Guides in Metrology (JCGM).

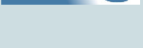
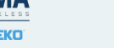
Network Science: accurate and high-resolution measurements

- Large expenses in equipment acquisition
- Large expenses in equipment maintenance
- Large expenses in equipment technicians
- Time consuming preparation
- **Unsuitable to achieve individually!!**

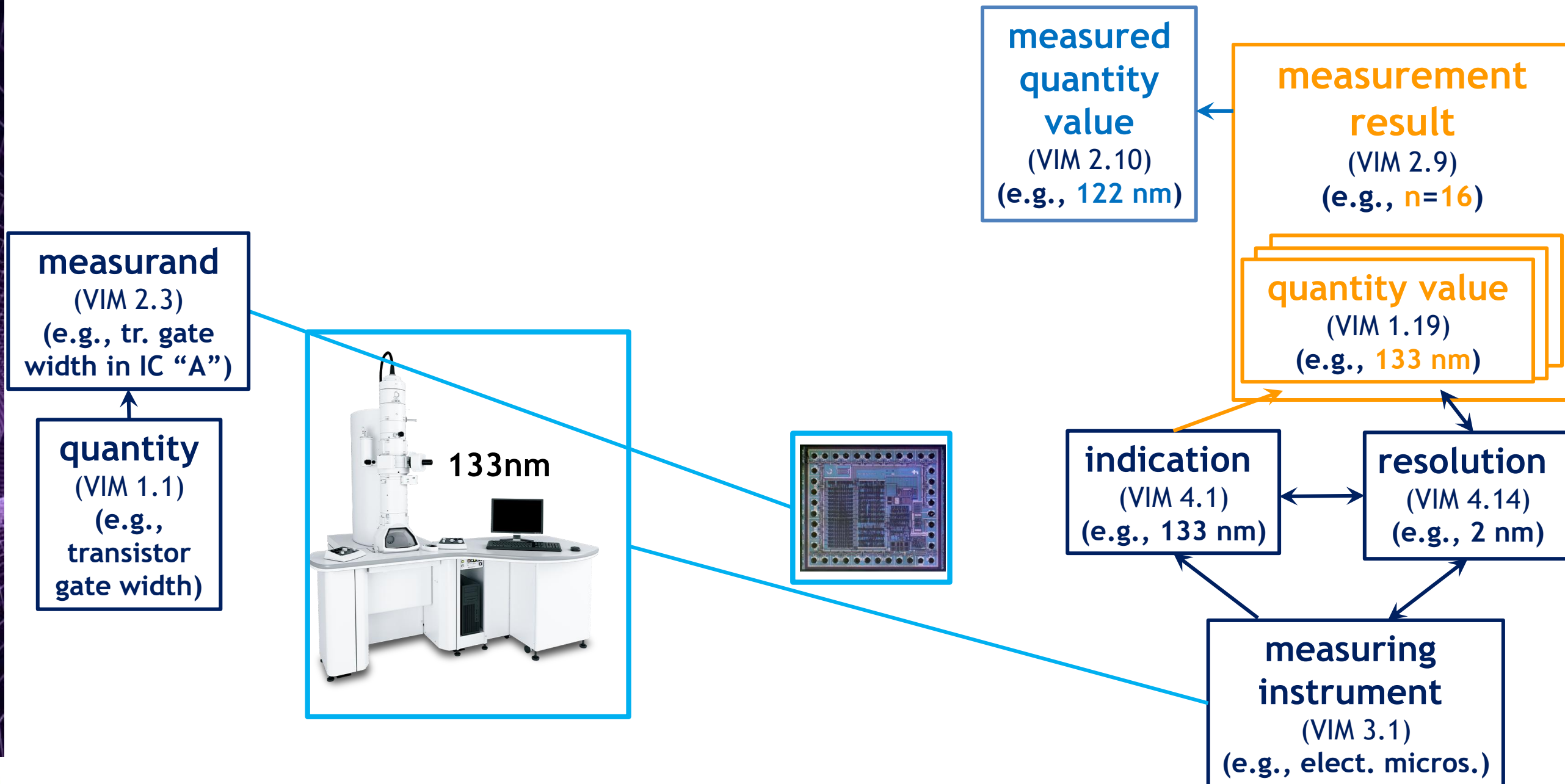


ESFRI-SLICES $\Leftrightarrow$ single set of laboratories for network science for all Europe!



Countries	Government	Research and Academia		Industry	Clusters, networks and others	NRENs	Worldwide support
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	Flemish conditional support + Walloon financial support to a linked project			 			
		 		 			
	 			 			
		  		 			
				 			
	Local support confirmed			 			
		 		 			
				 			
		   		 			
				 			
			 	 			
		 		 			
				 			
		  	 	 			

Network Science: accurate and high-resolution measurements



We can predict the future!



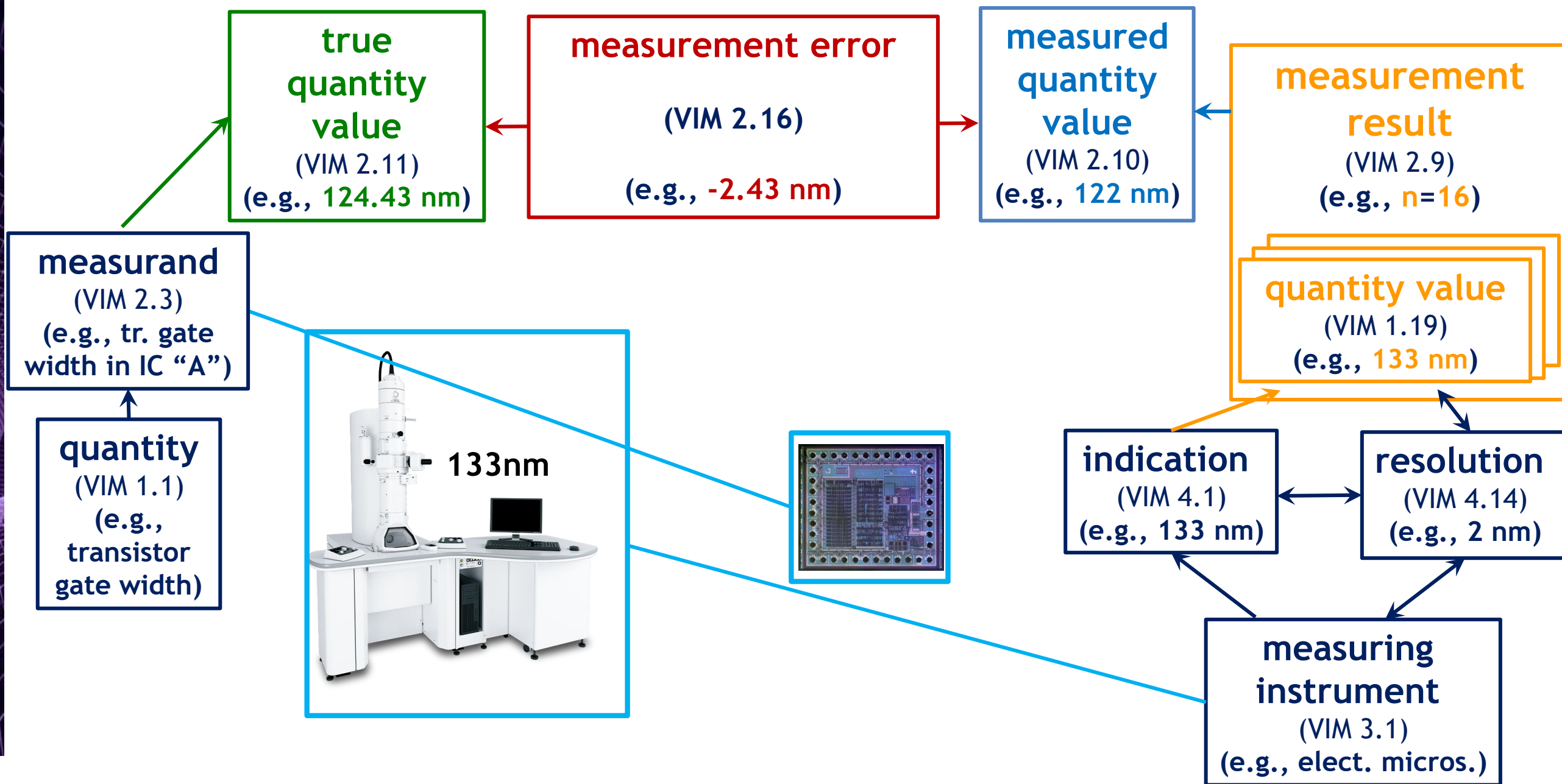
Pierre-Simon Laplace

1749-1827

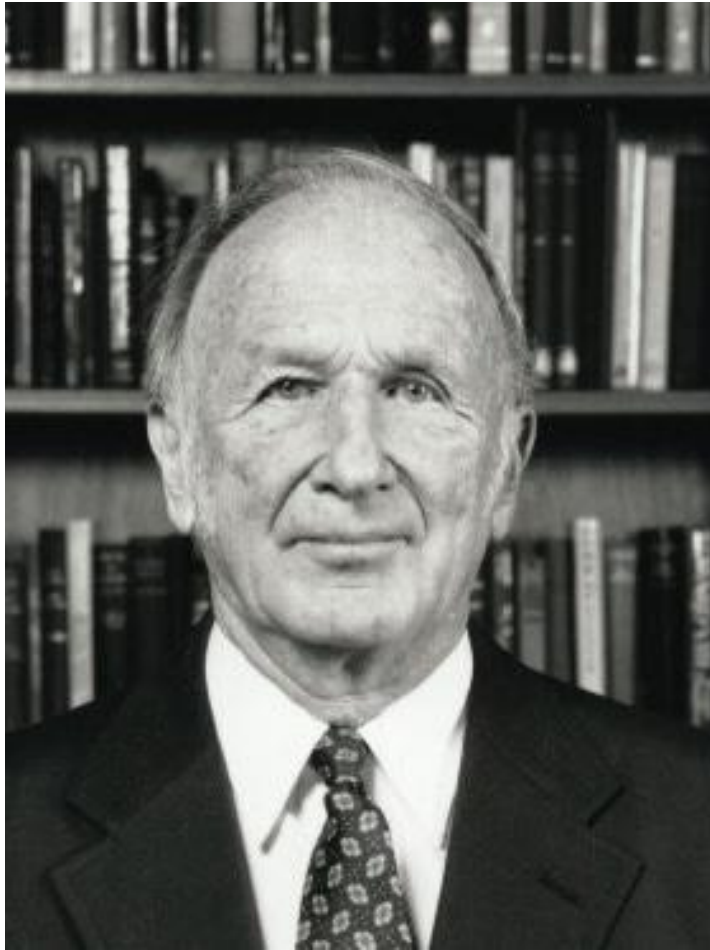
Determinism

Once we know all the laws of
physics, and the required math
to formalize them,
we can predict the future
and
we can find out the past

Measurement error



We cannot predict the future!



Edward Lorenz

1917-2008

Chaos theory

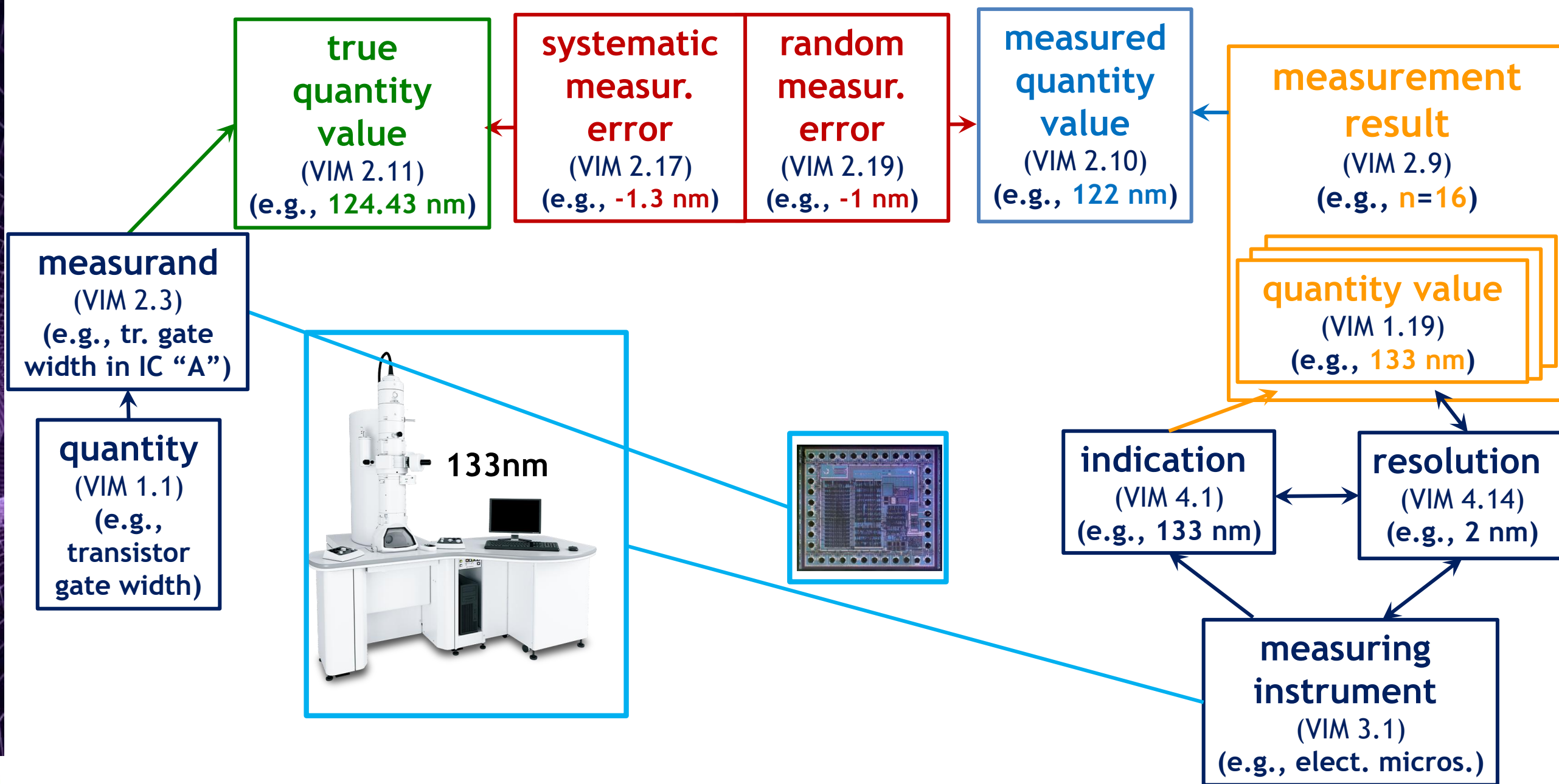
Predicting is fine for linear deterministic systems, where a percentual error in the initial conditions causes a similar percentual error in the result

but...

for non-linear deterministic systems, a **tiny error** in the initial conditions can cause a **HUGE error** in the result!

Actually, many non-linear deterministic systems exhibit a **pseudo-random** behavior

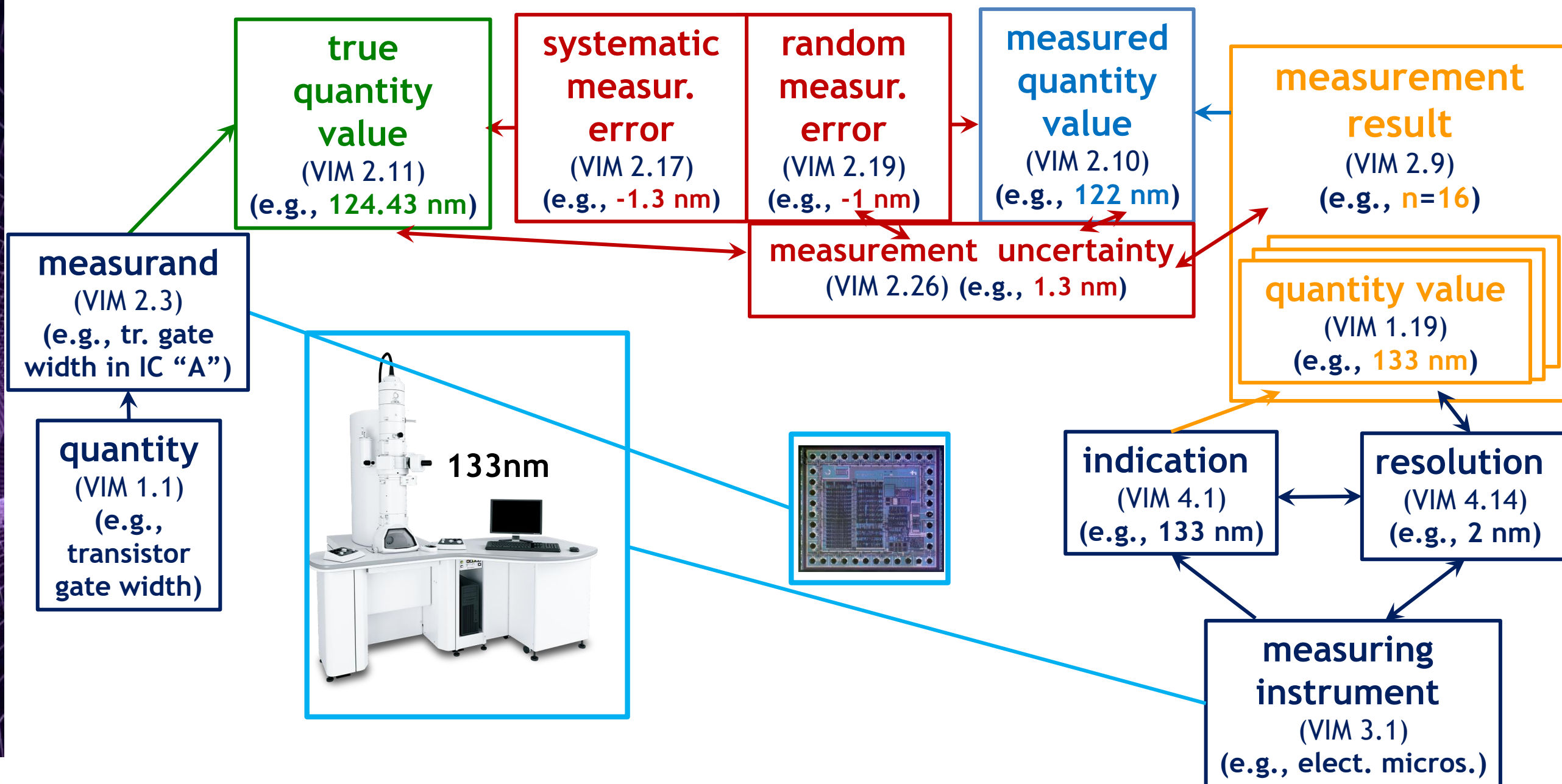
Systematic error and random error



Systematic measurement error

- VIM 2.17 “*systematic measurement error: component of measurement error that in replicate measurements remains constant or varies in a predictable manner*”
- It is the **true mean** of the individual **random measurement errors** minus the **true quantity value**
- If we know the causes, we can on some cases suppress them
- Regardless of our knowing the causes or not, if we can **estimate** the **value** of the **systematic measurement error**, we can apply a **correction**

Uncertainty quantifies the random error



The uncertainty can be reduced!

14

- **Uncertainty** manifests because “ n_M ” repeated measurements over the same measurand result in different **quantity values**
- This is modeled as a random variable “ M ” with unknown distribution
- The **measurement result** “ mr_M ” is a sample of “ n_M ” realizations of “ M ”, which are “ $q_val_{M,i}$ ” with “ $i=1$ to n_M ”. This sample is used to produce:
 - Estimated average of “ M ”: $\mu_M \sim \text{avg}(mr_M) = \sum_{i=1}^n q_val_{M,i}$ (arithmetic average)
 - **Standard deviation** of the **measurement result**:
 $(mr) = [\sum_{i=1}^n (q_val_i - \text{avg}(mr_M))^2 / (n_M - 1)]^{1/2}$ (std of the sample)
 - Estimated **standard deviation** of “ M ”:
 $\sigma_M \sim (\text{imu}_M^2 + \text{std}(mr_M)^2)^{1/2}$ (root-sum-square)
 where “ imu_M ” is the standard **instrum. meas. uncertainty** (if known)
- The **combined std. meas. uncertainty** (VIM 2.31) of our **measured quantity value** may be reduced by properly averaging the “ n_M ” **quantity values**

Why and how much does averaging reduce the uncertainty?

- **Lindeberg-Lévy CLT:** for a large number “ n_M ” of random variables “ M_1 ”, “ M_2 ”, ..., “ M_n ”, all with mean “ μ_M ” and standard deviation “ σ_M ”, the distribution of the random variable of their average “ $AM = \text{avg}(M_1, M_2, \dots, M_{n_M})$ ” tends to a Gaussian with mean “ $\mu_{AM} = \mu_M$ ” and standard deviation “ $\sigma_{AM} = \sigma_M / \sqrt{n_M}$ ”
- **Lindeberg-Feller CLT:** for a large number “ k ” of random variables “ AM_1 ”, “ AM_2 ”, ..., “ AM_k ”, with mean “ μ_{AMj} ” and standard deviation “ σ_{AMj} ”, the distribution of the random variable of their average “ $AAM = \text{avg}(AM_1, AM_2, \dots, AM_k)$ ” tends to a Gaussian with mean “ $\mu_{AAM} = \sum_{j=1}^k \mu_{AMj} / k$ ” (arithmetic average) and standard deviation “ $\sigma_{AAM} = (\sum_{j=1}^k \sigma_{AMj}^2)^{1/2} / k$ ” (root-sum-square divided by “ k ”)
- But only if the averaged random variables are:
 - Independent
 - Having finite variance
 - Lindeberg-Lévy: identically distributed
 - Lindeberg-Feller: $\forall \varepsilon > 0, \lim_{k \rightarrow \infty} \frac{1}{(k\sigma_{AAM})^2} \sum_{j=1}^k E[(AM_j - \mu_{AMj})^2 \cdot \mathbf{1}_{\{|AM_j - \mu_{AMj}| > \varepsilon \cdot (k\sigma_{AAM})^2\}}] = 0$ (no dom. variances)

But...what is a “large” number “ n_M ”?

16

The number of **quantity values** “ n_M ” is a critical factor:

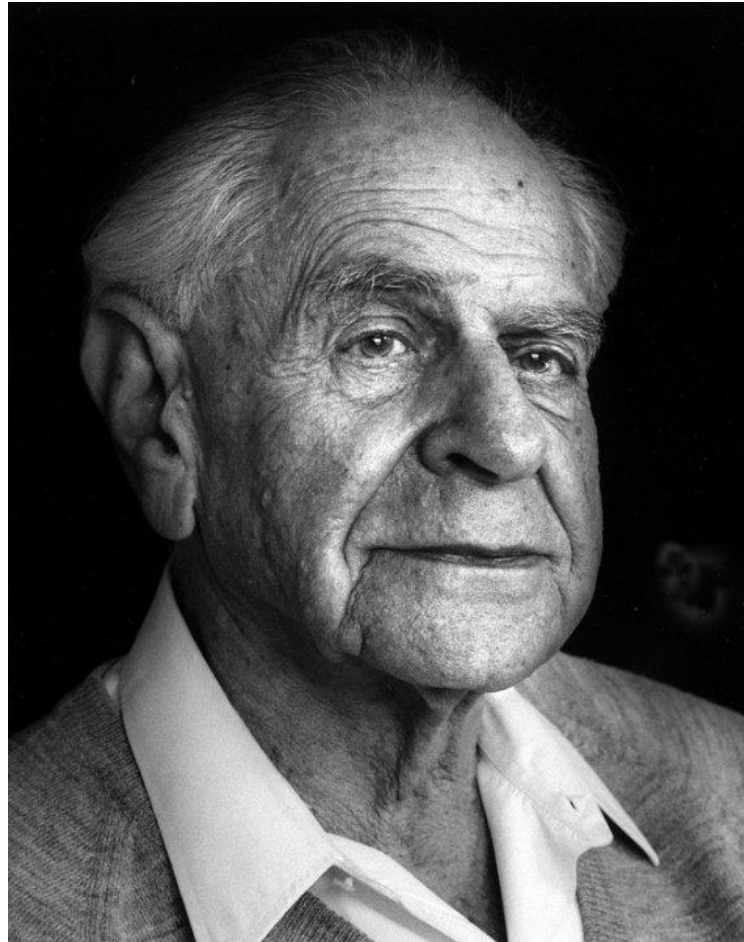
- $n_M = 1 \Rightarrow u_{AM} = \sigma_{AM} = \sigma_M \sim$ **instrumental meas. uncer.**
- $n_M < 30 \Rightarrow$ better **mqv** $_{AM}$, but similar **uncertainty**
 $u_{AM} = \sigma_{AM} = \sigma_M \sim (\text{imu}_M^2 + \text{std}(\text{mr}_M)^2)^{1/2}$
- $n_M \geq 30 \Rightarrow$ minimum for central limit theorem validity $\Rightarrow$
uncertainty reduction: $u_{AM} = \sigma_{AM} = \sigma_M / \sqrt{n_M}$
- $n_M \sim 100 \Rightarrow$ used in high-precision laboratories
- $n_M \sim 1,000 \Rightarrow$ used in industrial calibration
- $n_M \sim 10,000 \Rightarrow$ non-parametric estimation of a PDF,
including detection of a **pathological** distribution

Descartes' scientific method



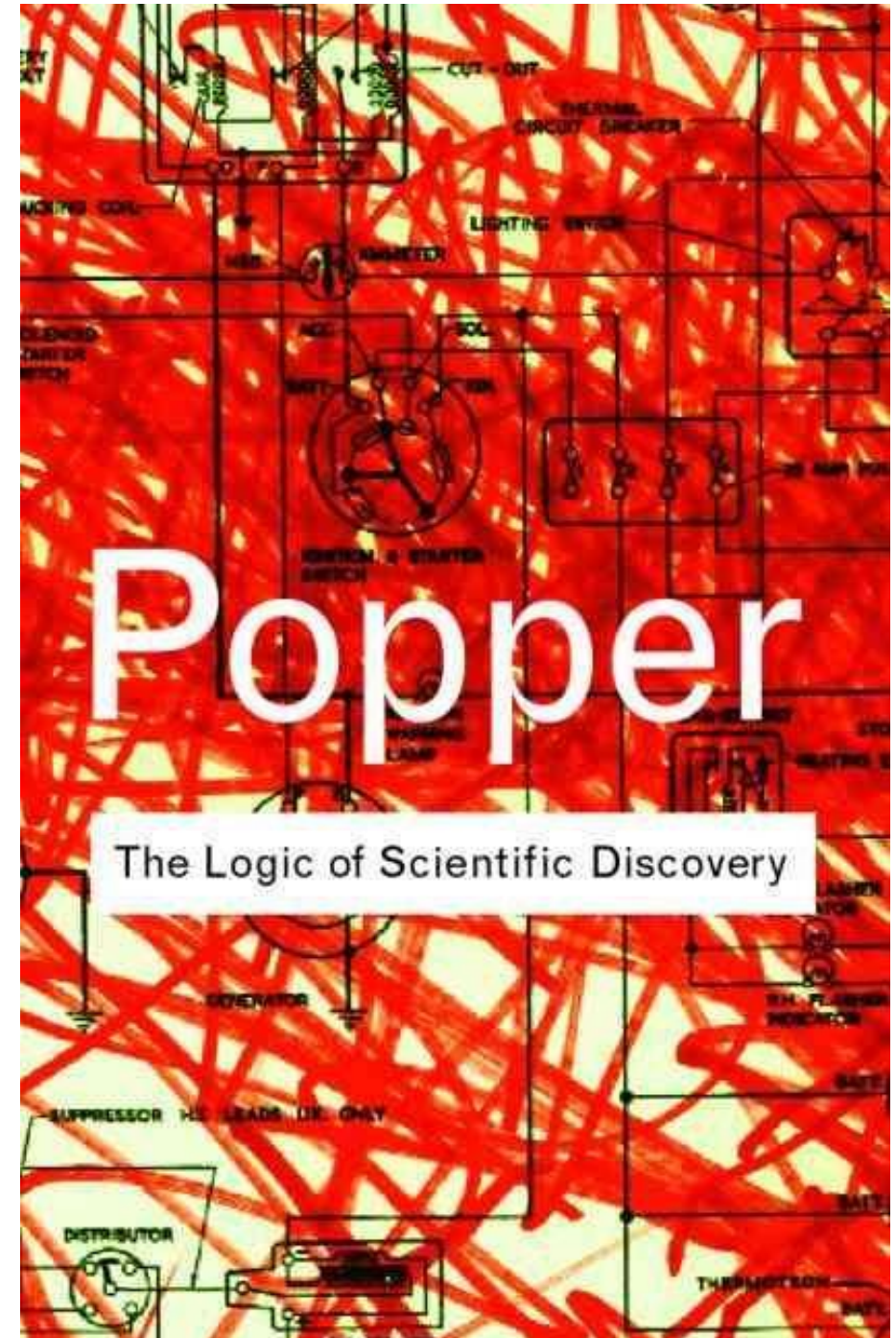
- In math, deductive reasoning: use general logic laws to proof each particular Theorem
- In physics, inductive reasoning: use particular observations to infer a general law
 - No one has ever seen a cell in neural tissue => there are no cells in neural tissue

We can be quite
certain about things!



Karl Popper

1902-1994



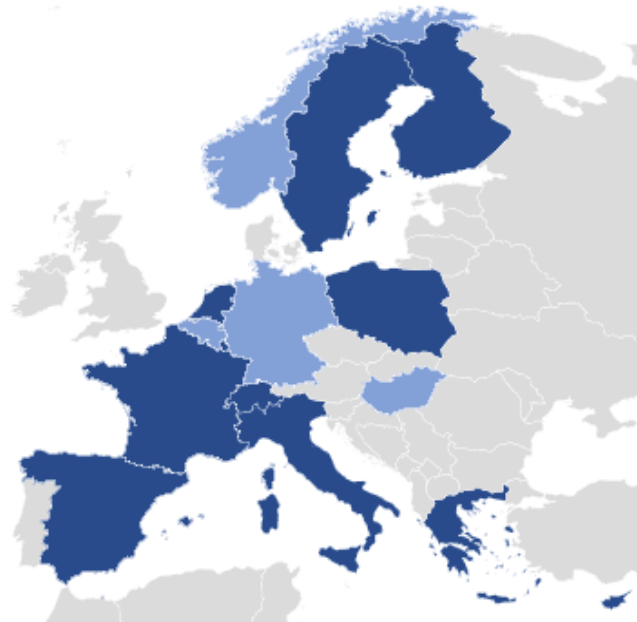
Popper's postulates

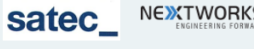
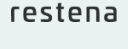
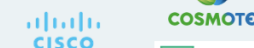
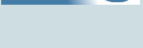
- Deductive reasoning can be **foolproof**
 - Math, engineering, ...
- Inductive reasoning can never be foolproof
 - Falsification of a **physical law**: only 1 case required =>
“*The black swan*” => Ramón y Cajal sees neurons => neurons exist!
 - Certainty of a **physical law**: infinite measurements, with infinite accuracy in an infinite set of environmental conditions => impossible
 - The **best** science can do is provide a confidence **proportional** to the quantity of successful verifications of the **physical law** => reproducibility
 - Some principles to build bridges have been verified over **thousands of years** throughout the world => we can be **very certain** that they are correct

Measurement repeatability and reproducibility

- **measurement repeatability** (VIM 2.21 and VIM 2.20)
Degree of closeness of several **measured quantity values** (or several **quantity values**), over the same or similar measurands, with the same measuring system, same measuring procedure, same operating conditions, same operators, same location and over a short period of time.
- **measurement reproducibility** (VIM 2.25 and VIM 2.24)
Degree of closeness of several **measured quantity values** (or several **quantity values**), over the same or similar measurands, with a different measuring system and/or a different measuring procedure and/or different operating conditions and/or different operators and/or a different location and/or over a long period of time.
- **Reproducibility** is a fundamental cornerstone of empirical sciences

ESFRI-SLICES <=> Reproducibility



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Pan-European effort: ESFRI-SLICES

- Europe is behind the US, China and Korea/Japan in networking technology
- Networks are the nervous system of Europe: without them, all activity paralyzes
- Networks are essential for Europe's defense: the Ukraine war is proving this every day
- European networking technology is essential for Europe's autonomy
- SLICES will provide a single set of world-top laboratories for networking technology: essential for accurate and high-resolution measurements
- SLICES will allow for reproducibility of experiments: essential for sound scientific results

Thanks for your attention!!!

