Measurement Uncertainty and Significant Figures

Measured values are never exact: instrument, operator, environment, definition

Roadmap: error vs. uncertainty, resolution, sig figs, rounding, propagation, reporting

Stakes: lab reproducibility, regulatory thresholds, clinical decisions, engineering tolerances

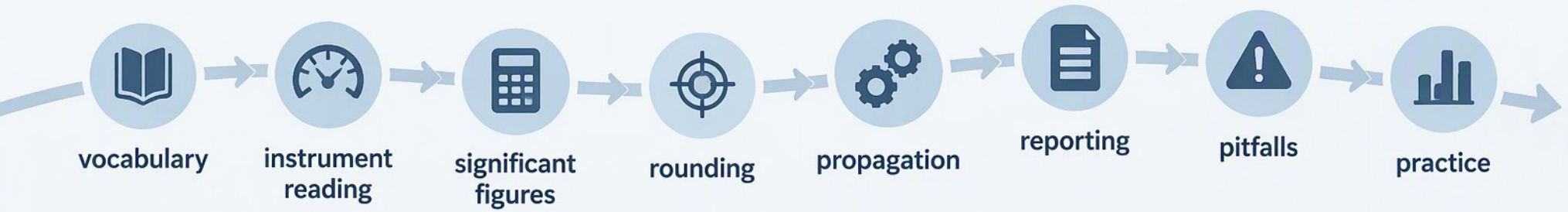
Outcome: interpret, calculate, and communicate measurement precision correctly

Honest precision claims matter in study, teaching, and lab work

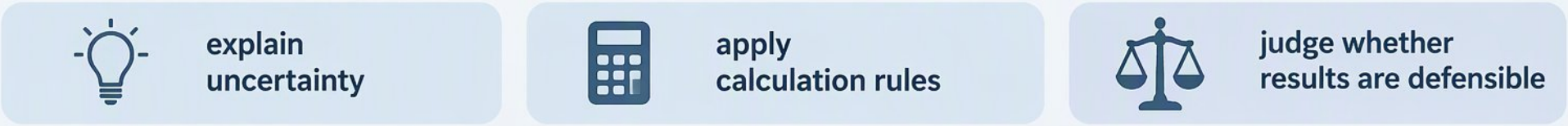


Course Roadmap and Learning Targets

- **Sequence:** vocabulary → instrument reading → significant figures → rounding → propagation → reporting → pitfalls → practice



- **Three levels:** explain uncertainty, apply calculation rules, judge whether results are defensible



- **Pathways:** students apply in labs; teachers map misconceptions; learners build interpretation skills

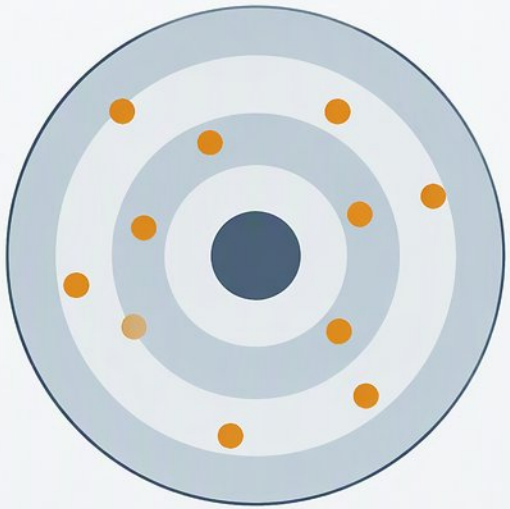


- **End goal:** turn a raw measurement into a defensible value ± uncertainty statement



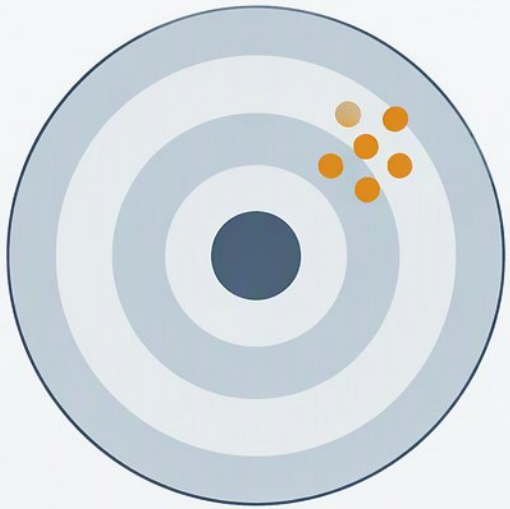
Error, Accuracy, and Precision: Clearing Up the Vocabulary

- Systematic error shifts results consistently in one direction; random error scatters results around a center
- Accuracy vs. precision vs. trueness: the target diagram separates bias from scatter
- An error is unknowable in practice; an uncertainty is estimable and reportable
- Type A: from repeated measurements (statistics); Type B: from specifications, calibration, and judgment



Random error

Scatters results around a center

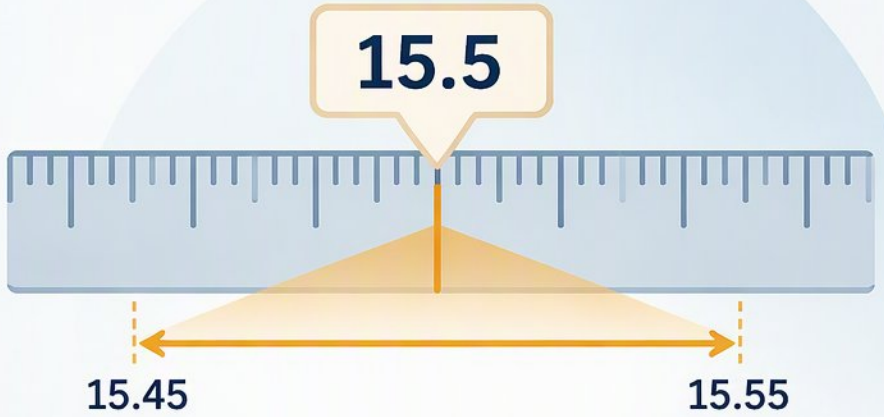


Systematic error

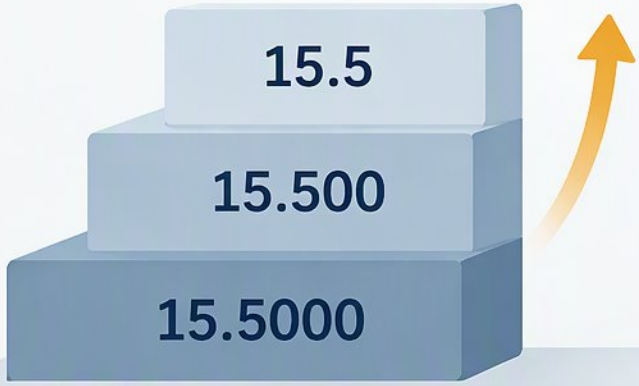
Shifts results consistently in one direction

Why ‘More Decimals’ Does Not Mean ‘More Accurate’

- Extra decimal places look precise but can mislead readers
- More digits often boost confidence while lowering correctness
- Writing 15.5 secretly implies a range of 15.45 to 15.55
- Explicit uncertainty removes ambiguity: 15.5 ± 0.05
- Bonus digits cannot create precision the instrument lacks



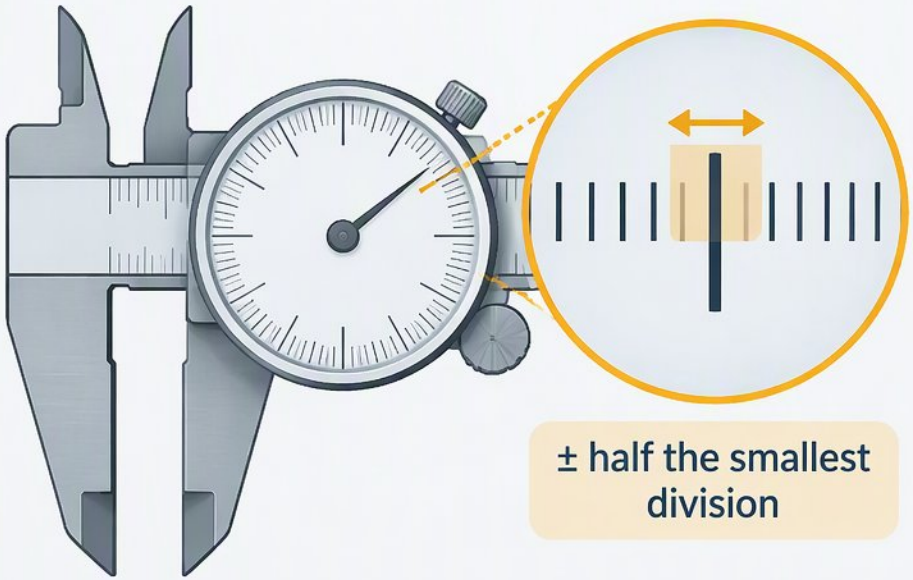
15.5 ± 0.05



More digits often look more precise, but are not more accurate.

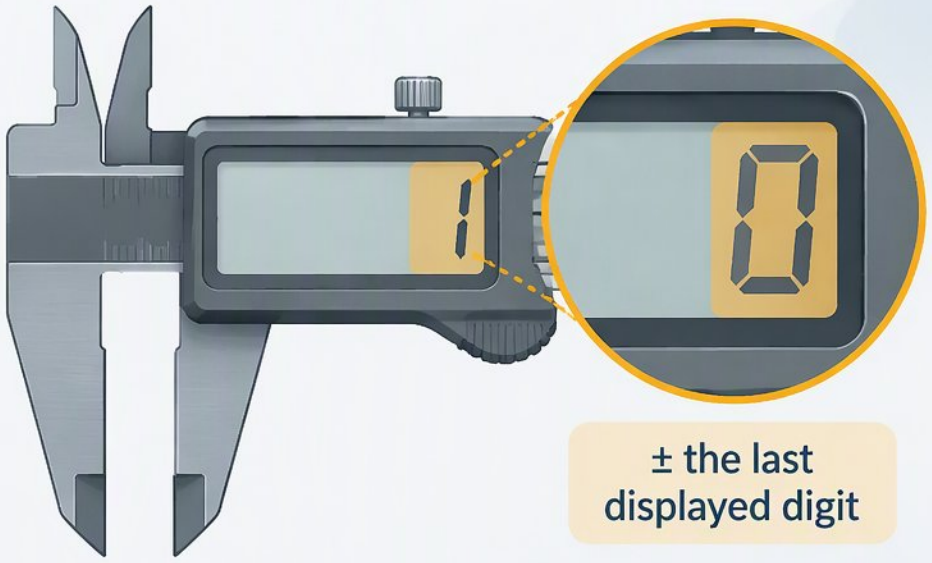
Instrument Resolution and Reading Uncertainty

- Resolution, readability, and least count differ between analog and digital instruments
- Analog rule of thumb: ± half the smallest division; digital: ± the last displayed digit
- Manufacturer specifications and calibration certificates can override simple rules
- Practical check: choose instrument resolution appropriate to the required tolerance, not the highest available



± half the smallest division

Analog Instrument



± the last displayed digit

Digital Instrument

Significant Figures: What They Encode

MEASURE
THINK
APPLY
SUCCEED



- Significant figures encode measurement precision, not decoration
- Non-zeros and captive zeros always count as significant
- Leading zeros never count; trailing zeros count only with a decimal
- Exact and counting numbers have unlimited significance; measurements do not
- Scientific notation removes ambiguity: 1.20×10^3 states three significant figures

EXAMPLES

0.0073	12.0	100	2,304	1.20×10^3
Leading zeros do not count	Trailing zero counts with a decimal	Trailing zeros do not count (without a decimal)	Non-zeros and captive zeros always count	Three significant figures
2 significant figures	3 significant figures	1 significant figure	4 significant figures	3 significant figures

SAME NUMBERS. DEEPER UNDERSTANDING.

A Meaning-First Approach to Teaching Significant Figures



- Begin with familiar measurements, not memorized rule lists
- Implied relative uncertainty explains significance without rote rules
- Students learn better as active participants than passive note-takers
- Surface outdated textbook beliefs about special cases and trailing zeros
- Tie each rule back to the physical act of reading an instrument

Rounding and Arithmetic with Significant Figures

Type of operation?

Multiplication and division

- Keep the fewest significant figures in the result.

Addition and subtraction

- Keep the fewest decimal places instead.

Defer all rounding until the final answer to prevent drift.

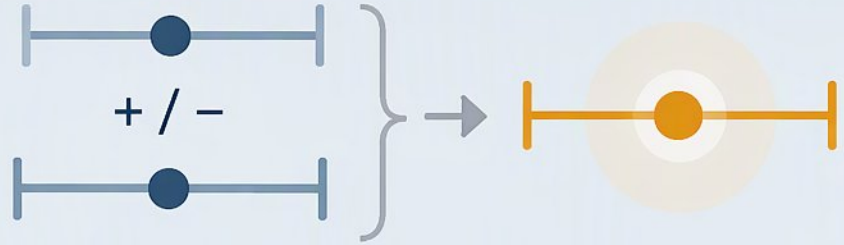
- Mixed operations: apply each rule per step, but round only at the end.
- Example: 3.457 W × 5.60 s = 19.3292 J, reported as 19.3 J.

Propagating Uncertainty Through Calculations

- **Absolute uncertainty:** same units as the quantity; relative uncertainty: fraction or percent
- **Addition and subtraction:** combine absolute uncertainties in quadrature
- **Multiplication and division:** combine relative uncertainties in quadrature
- **Powers and roots:** relative uncertainty scales with the exponent
- Identify the dominant contributor to focus improvement efforts

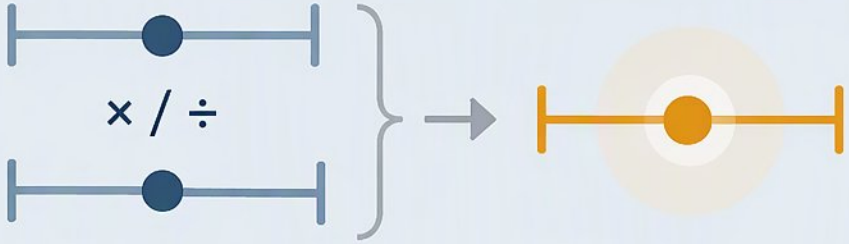
Addition and Subtraction

Combine absolute uncertainties in quadrature



Multiplication and Division

Combine relative uncertainties in quadrature





Identify the dominant contributor to focus improvement efforts

Reporting Results That Communicate Precision

- **Format:** value ± expanded uncertainty with units, e.g., 9.81 ± 0.02 m/s²

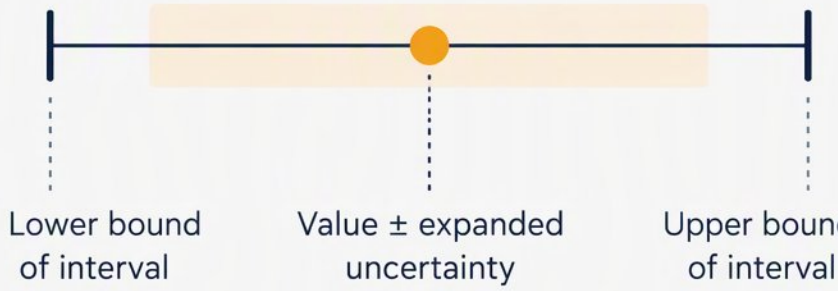
- **Match decimal places** between value and uncertainty; quote uncertainty to one or two significant figures

- **Coverage factor k** (e.g., k = 2, about 95%) states the confidence level attached to the interval

- **Avoid over-reporting** and under-reporting; relative uncertainty in percent is more informative in some comparisons

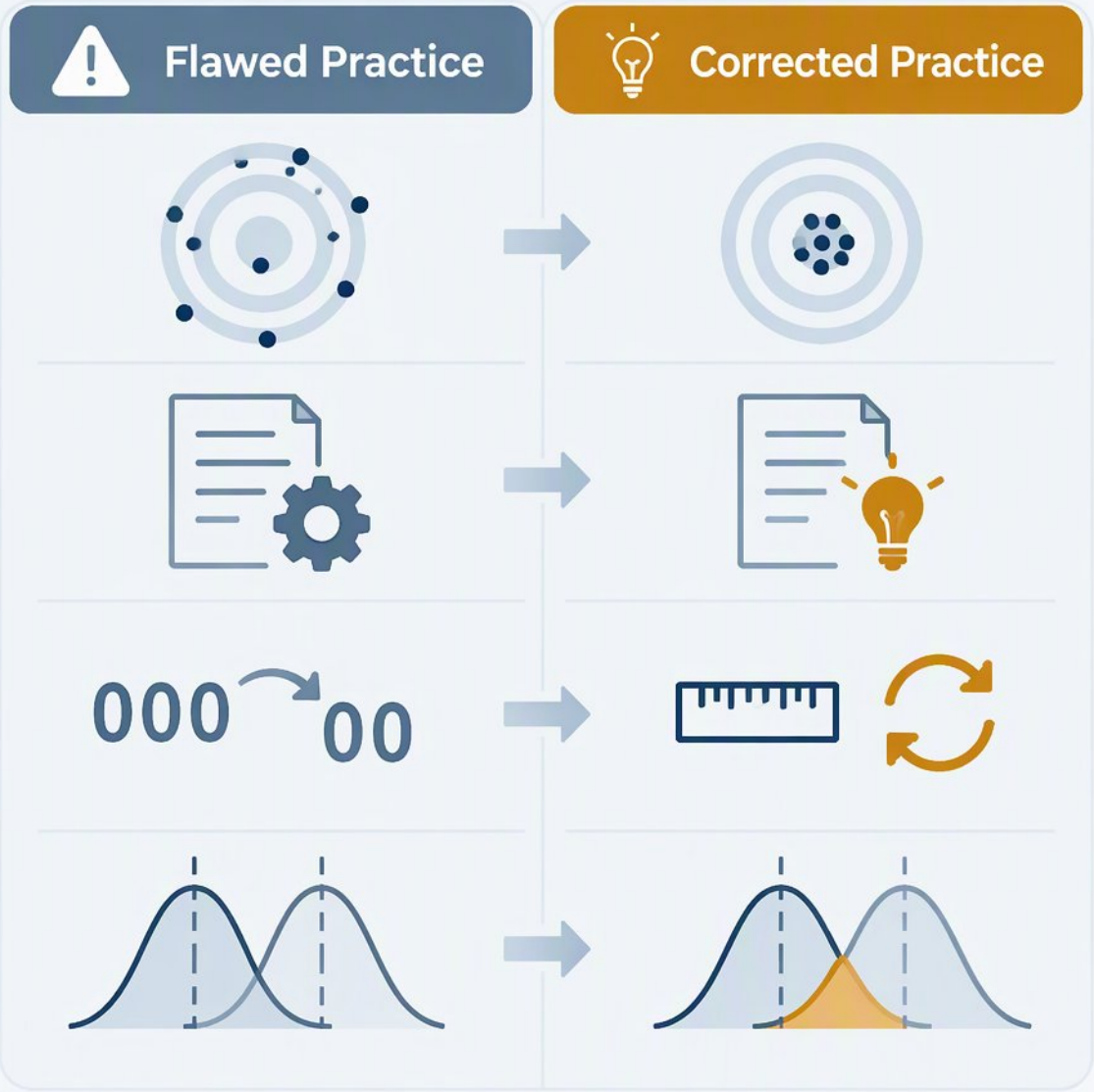
SPECIMEN REPORTING CARD

9.81 ± 0.02 m/s²



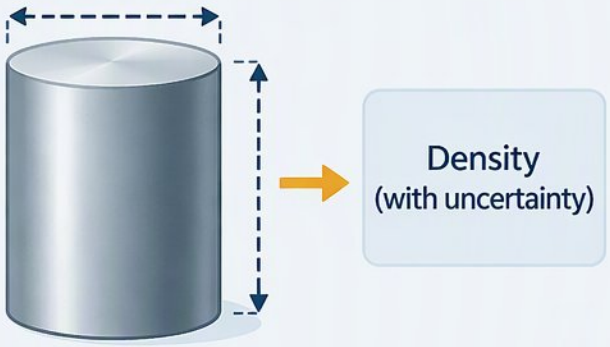
Common Pitfalls and Misconceptions

- Confusing precision with accuracy; treating human error as random uncertainty
- Applying sig-fig rules mechanically where full propagation is needed
- Trailing-zero traps, double rounding, unit conversions, and absolute/relative mixing
- Students know the terms but still judge agreement from means alone
- Instruction must target use, not just recall

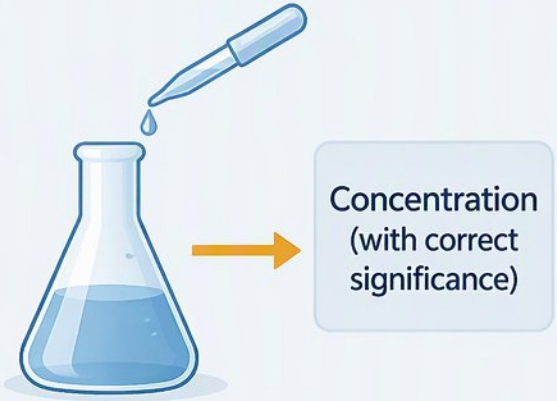


Hands-On Practice: Worked Examples and Mini-Exercises

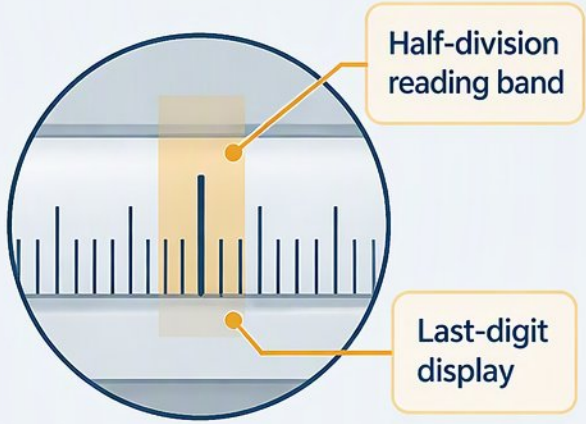
Scenario 1: measure a metal cylinder, propagate uncertainty into density



Scenario 2: prepare a solution, report concentration with correct significance



Instrument Reading

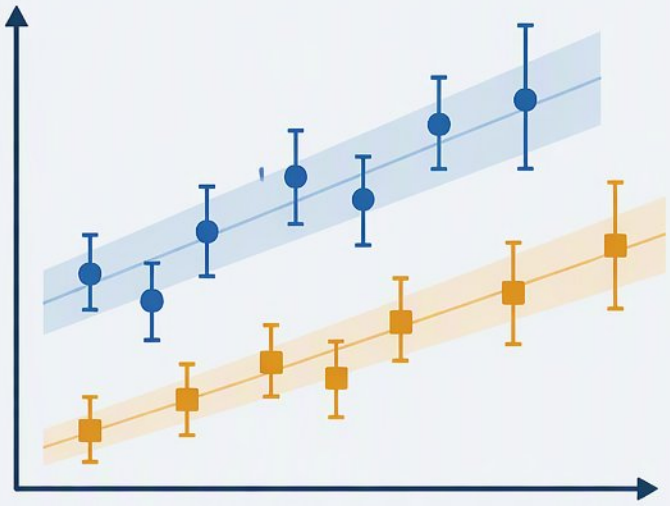


Mini-quiz: count significant figures, round results, format uncertainty statements

Peer review: evaluate a reported result, justify each improvement

Rationales trace back to reading, rounding, propagation, and reporting rules

Designing Uncertainty-Aware Lab Activities



Teacher checklist:

- ☑ check significant figures
- ☑ and uncertainty statements



- Compare two data sets, not one against a textbook value
- Use graphs to reduce cognitive load and show spread
- Teacher checklist: check significant figures and uncertainty statements
- Calibration exercises, like checking a balance, link uncertainty to decisions
- Task example: measure metal cylinder and propagate uncertainty into density

Standards, Takeaways, and Further Reading

MEASUREMENT
FOR A MORE
CERTAIN TOMORROW



Key Takeaways

- JCGM/VIM and the GUM suite frame uncertainty internationally
- 2026 Amendment 1 addresses nonlinearity in measurement models
- ISO/IEC 17025 accredited testing requires documented uncertainty statements
- Report explicit uncertainty and never let format overstate method precision

Further reading: BIPM/JCGM documents, NIST guidance, discipline norms

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