“Quantum Sensing”*)
— Sec. I & II —

K. Suzuki

*) C.L. Degen, F. Reinhard and P. Cappellaro, Rev. Mod. Phys. 89, 035002 (2017)

Sec. I Introduction (1)

- *Promising real-world applications of quantum mechanics?*
  - *Quantum computers,*
    - *Deutsch, D., 1985, Proc. R. Soc. A 400, 97.*
    - *DiVincenzo, D. P., 2000, Fortschr. Phys. 48, 771.*
  - *Quantum cryptography,*
    - *Gisin, N., G. Ribordy, W. Tittel, and H. Zbinden, 2002, Rev. Mod. Phys. 74, 145.*
  - *Quantum sensors.*
    - *For magnetic and electric fields, time and frequency, rotations, temperature and pressure.*
    - *Capitalize on the central weakness of quantum systems, their strong sensitivity to external disturbances.*

      →This trend in quantum technology is curiously reminiscent of the history of semi-conductors.
      - *Sensors have found commercial applications decades before computers.*
      - *e.g. light meters based on selenium photocells: Weston, E., 1931, "Exposure Meter," U.S. Patent 2016469.*

Sec. I Introduction (2)

- *Many concepts of quantum sensing have resulted from decades of development in high-resolution spectroscopy.*
  - *In atomic physics and magnetic resonance, especially.*
    - *e.g. atomic clocks, atomic vapor magnetometers and superconducting quantum interference devices.*
- *What's "new" in quantum sensing?*
  - *Quantum systems are increasingly investigated at the single-atom level,*
  - *Entanglement is used as a resource for increasing the sensitivity,*
  - *Quantum systems and quantum manipulations are specifically designed and engineered for sensing purpose.*
- *This review focuses on key concepts and methods of quantum sensing.*
  - *With particular attention to practical aspects that emerge from nonideal experiments.*
  - *Will consider mostly "qubits" — two-level quantum systems.*
    - *Will overview actual implementations, but not in specific detail.*
    - *Will not cover related fields, e.g. atomic clocks or photon-based sensors.*
    - *Will consider theory only up to the point necessary to introduce the key concepts.*
- *This review intends to …*
  - *Offer an introduction to whom new to the field,*
  - *Provide a basic reference for whom already active in the field.*

Sec. I.A Content (1)

- *Some basic definitions for "quantum sensing" (Sec. II.A).*
- *The elementary criteria for a quantum system to be useful as a quantum sensor (Sec. II.B).*

- *An overview of the most important physical implementations (Sec. III).*
- *The core concepts of quantum sensing:*
  - the basic measurement protocol (Sec. IV),
  - the sensitivity of a quantum sensor (Sec. V).

Sec. I.A Content (2)

- *Covering the important area of*
  - *time-dependent signals (Sec. VI),*
  - *quantum spectroscopy (Sec. VII).*

- *Some advanced quantum sensing techniques:*
  - *adaptive methods developed to greatly enhance the dynamic range of the sensor (Sec. VIII),*
  - *techniques that involve multiple qubits (Secs. IX and X), particularly the entanglement-enhanced sensing, quantum storage, and quantum error correction (QEC) schemes.*

- *A brief outlook on possible future developments (Sec. XI).*

Sec. I.A Content (3)

- *Several reviews that covered different aspects of quantum sensing and excellent introductions into the field.*
  - *A review:*
    - *Budker, D., and M. Romalis, 2007, Nat. Phys. 3, 227.*
  - *A book on atomic vapor magnetometry:*
    - *Budker, D., and D. F. J. Kimball, 2013, Optical Magnetometry (Cambridge University Press, Cambridge, UK).*
  - *A paper on magnetometry with nitrogen-vacancy centers in diamond:*
    - *Taylor, J. M., P. Cappellaro, L. Childress, L. Jiang, D. Budker, P. R. Hemmer, A. Yacoby, R. Walsworth, and M. D. Lukin, 2008, Nat. Phys. 4, 810.*
  - *Papers on entanglement-assisted sensing, sometimes referred to as "quantum metrology," "quantum-enhanced sensing," or "second generation quantum sensors":*
    - *Bollinger, J. J.,W. M. Itano, D. J.Wineland, and D. J. Heinzen, 1996, Phys. Rev. A 54, R4649.*
    - *Giovannetti, V., S. Lloyd, and L. Maccone, 2004, Science 306, 1330.*
    - *Giovannetti, V., S. Lloyd, and L. Maccone, 2006, Phys. Rev. Lett. 96, 010401.*
    - *Giovannetti, V., S. Lloyd, and L. Maccone, 2011, Nat. Photonics 5, 222.*

Sec. II.A Quantum sensing

- *Quantum sensing is one of the following:*
  (I) Use of a quantum object to measure a physical quantity (classical or quantum).
    - *"Quantum object": characterized by quantized energy levels,*
    - *Such as electronic, magnetic or vibrational states of …*
    - *Superconducting or spin qubits, neutral atoms or trapped ions.*

  (II) Use of quantum coherence to measure …
    - *"Quantum coherence": i.e. wavelike spatial or temporal superposition states.*

  (III) Use of quantum entanglement to improve the sensitivity or precision of a measurement.
    - *Sensitivity or precision beyond what is possible classically.*

- *Type I&II*
  - *Broadly cover many physical systems, including not-strictly-"quantum" ones.*
    - *e.g. classical wave interference in optical or mechanical systems.*
    - *Novotny, L., 2010, Am. J. Phys. 78, 1199.*
    - *Faust, T., J. Rieger, M. J. Seitner, J. P. Kotthaus, and E. M. Weig, 2013, Nat. Phys. 9, 485.*
  - *Often close to applications, → extensively discussed in this review.*
  - *May not exploit the full power of quantum mechanics, but already provide advantages:*
    - *e.g. operation at nanoscales that are not accessible to classical sensors.*
- *Type III*
  - *A truly quantum definition.*
  - *Relies on entanglement and, hence, requires >1 sensing qubits.*
    - *e.g. the use of maximally entangled states to reach a Heisenberg-limited measurement.*

Sec. II.B Quantum sensors (1)

From the criteria for quantum computation:

- *DiVincenzo, D. P., 2000, Fortschr. Phys. 48, 771.*

- *Four necessary attributes for a quantum system to be a quantum sensor:*

(1) Has discrete, resolvable energy levels.
  - *Will focus on a two-level system "qubit" (Fig. 1) (or an ensemble of two-level systems),*
  - *Through which many properties of more complex quantum systems can be modeled.*
  - *Goldstein, G., M. D. Lukin, and P. Cappellaro, 2010, arXiv:1001.4804.*

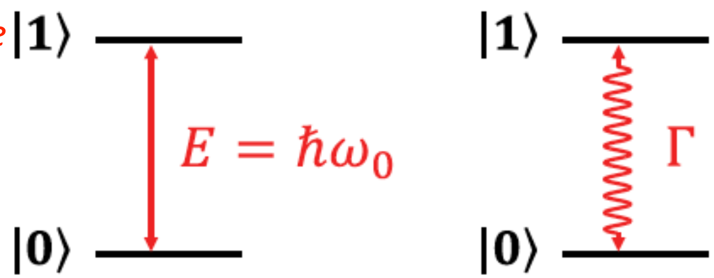
(2) Must be possible to initialize into a well-known state and to read out its state.

(3) Can be coherently manipulated, typically by time-dependent fields. (Not strictly required for all protocols.)
  - *Exception ex.: CW spectroscopy or relaxation rate measurements.*

(4) Interacts with a relevant physical quantity $V(t)$, such as an electric or magnetic field.
  - *Quantified by a coupling or transduction parameter $\gamma = \partial^q E/\partial V^q$ which relates changes in the transition energy E to changes in the external parameter V.*
  - *Coupling is mostly either linear ($q=1$) or quadratic ($q=2$).*
  - *Leading to a shift of the quantum system's energy levels or to transitions between energy levels (Fig. 1).*

The higher energy state

The lower energy state



Quantum sensing exploits changes in the transition frequency ω_0 or the transition rate Γ in response to an external signal V.

FIG. 1. Basic features of a two-state quantum system.

This review uses $\hbar = 1$ and expresses all energies in units of angular frequency.

Sec. II.B Quantum sensors (2)

- *Key physical characteristics to compare experimental realizations.*
  - *External parameter(s) they respond to.*
    - *Charged systems, e.g. trapped ions: electric fields,*
    - *Spin-based systems: magnetic fields,*
    - *Some systems: several physical parameters.*
  - *"Intrinsic sensitivity" (Eq. 1) → will see in Sec. V.*
    - *Strong response to wanted signals, while minimal influence of unwanted noise.*
    - *γ should be large, e.g. by the choice of an appropriate physical realization.*
    - *T_χ should be made as long as possible (to be discussed in the later sections).*

$$\text{sensitivity} \propto \frac{1}{\gamma\sqrt{T_\chi}}, \qquad (1)$$

γ (= $\partial^q E/\partial V^q$): transduction parameter

T_χ: decoherence or relaxation time