Consistent/Decoherent Histories

• Conceptual difficulties in QM come from introducing probabilities in the wrong way

• Histories approach: consistent introduction of probabilities eliminates difficulties and resolves (tames) paradoxes

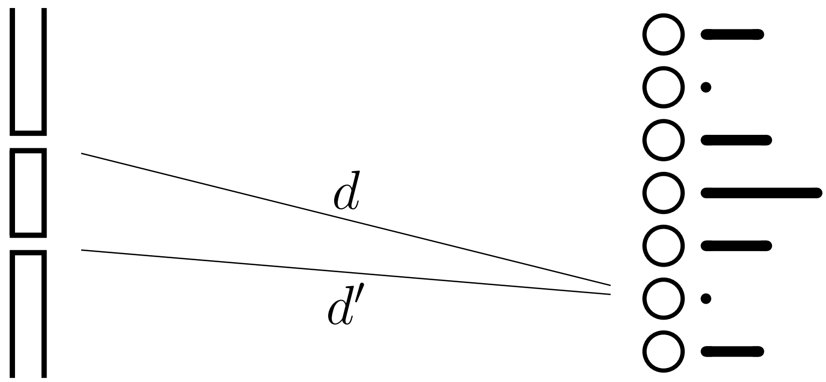
• History of histories:
  - ◦ Griffiths 1984
  - ◦ Omnès 1987
  - ◦ Gell-Mann and Hartle 1990
  - ◦ Many subsequent papers, books
  - ◦ Griffiths, CONSISTENT QUANTUM THEORY (Cambridge 2002). First 12 chapters available at:

    http://quantum.phys.cmu.edu/CQT

Histories and Paradoxes

- Paradoxes that are resolved/tamed using histories:
  - Einstein, Podolsky, Rosen
  - Double slit
  - Bell, Kochen, Specker
  - Greenberger, Horne, Zeilinger
  - Hardy
  - Aharonov and Vaidman multiple box
  - Wheeler delayed choice
  - Elitzur and Vaidman noninteracting measurement
  - ...
- Paradoxes that are not resolved using histories:
  - Any suggestions?

Double Slit I



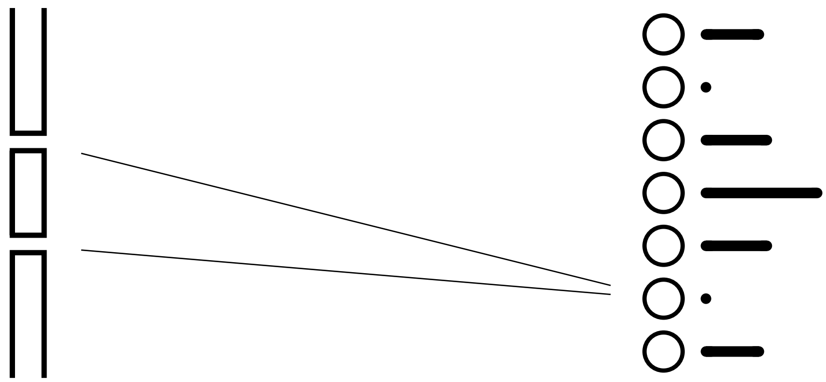
- Slit system, detectors in interference region
  - Horizontal bars: counting rates
  - Interference depends on *difference* $d - d'$, so
    – particles pass through slits *coherently*
  - Particles arrive *randomly* at detectors

- Consistent histories
  - Randomness an intrinsic part of nature
  - Anti-Einstein. There are no hidden variables

Histories and Measurements

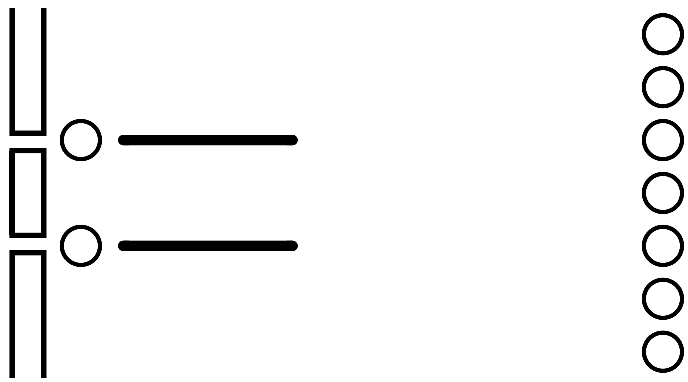
- Textbook QM:
  - Randomness arises through *measurements*
- Histories:
  - Randomness *intrinsic* in QM
  - Measurements are examples of physical processes
  - Same quantum principles govern *all* processes
  - There is *no* classical world, apparatus
  - *Sometimes* classical mechanics is a good approx
  - Quantum principles determine those circumstances

Double Slit II



- Experimentalist:
  - ◦ Detector triggers *because* particle arrives
  - ◦ Just *before* detection particle was near detector, on its way to detector
- Historian:
  - ◦ Good experimentalists know what they're doing
  - ◦ Triggered detector indicates arrival of particle
  - ◦ QM justifies this talk; indicates its limitations
  - ◦ Theorists should not bully competent people!

Double Slit III



- Detectors directly behind slits
  - Particles arrive at random
  - Total counting rate same as before
  - *One* detector, not both, detects each particle

- Explanations
  - Experimentalist:

Particle came through slit preceding detector—
Collimators work this way

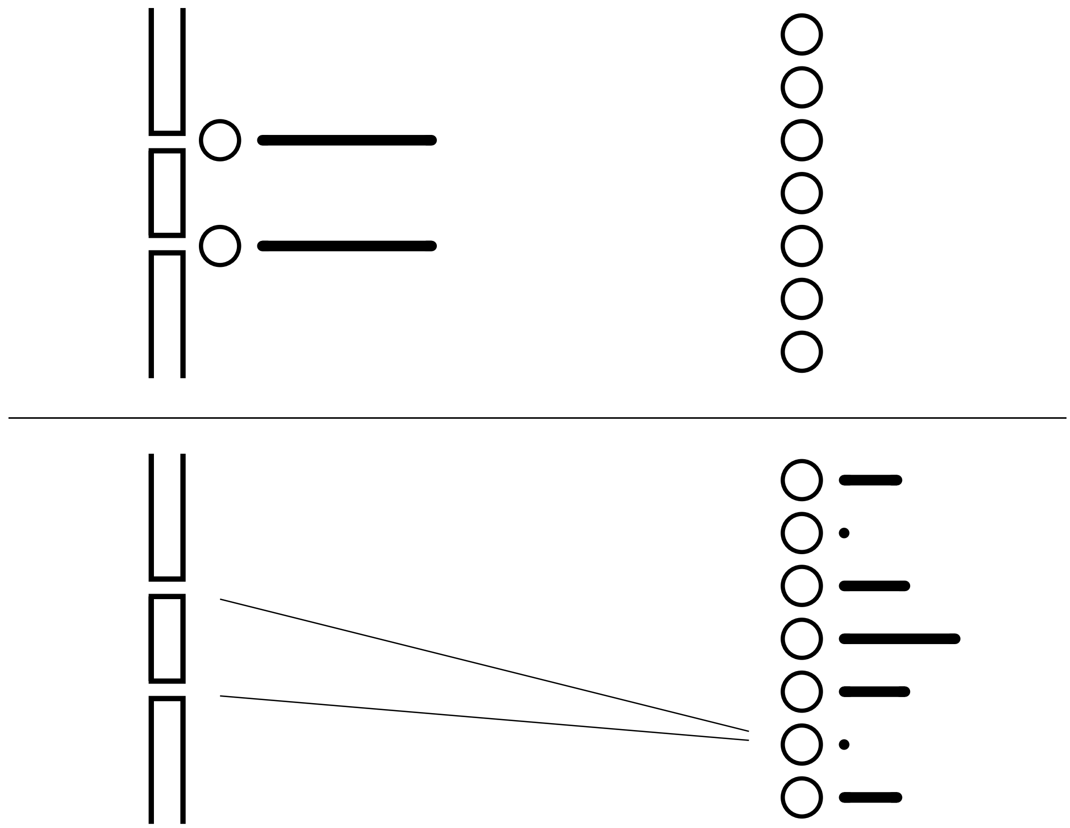
  - Textbook:

Cannot discuss what happened before measurement
"Great Smoky Dragon"

  - Historian:

QM supports experimentalist account

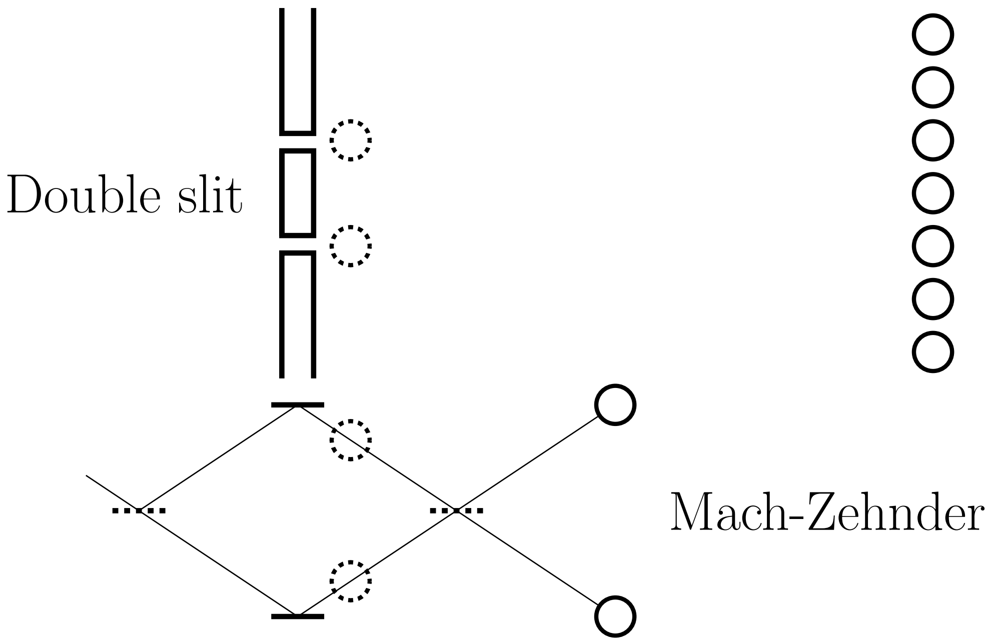
Double Slit IV



- Detectors behind slits removed at the last moment
    - Detectors remain:
        - particle came through definite slit
    - Detectors removed:
        - particle passed through slits coherently

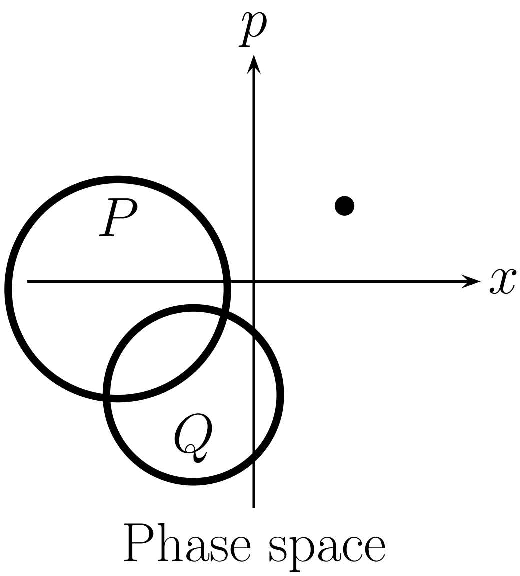
- Particle could enter slit system before decision to remove detectors was made! (Wheeler delayed choice)
    - Does the future influence the past?

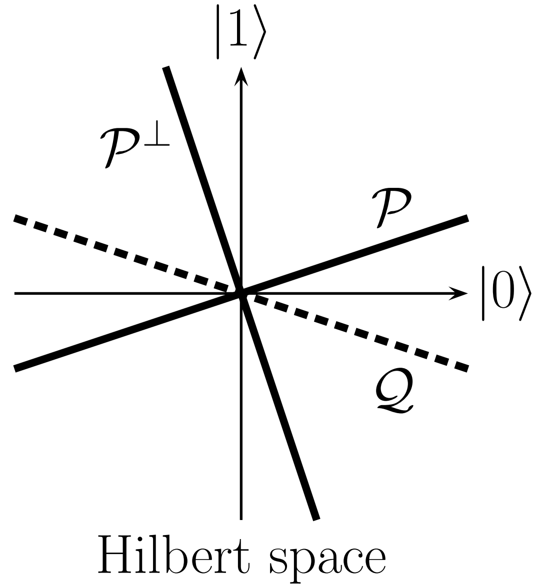
Double Slit + Mach-Zehnder



- Correspondences:
  - Which slit? ↔ Which arm?
  - Detectors behind slits ↔ inside interferometer
  - In interference zone ↔ following 2d beam splitter
- For precise description, use Mach-Zehnder
  - Basic idea applies to double slit

Phase Space and Hilbert Space





	Classical	Quantum
Physical state	Point	Ray
Property P	Subset P	Subspace $\mathcal{P}$
NOT P	Compl. $\sim P$	Orthog. compl. $\mathcal{P}^\perp$
P AND Q	$P \cap Q$	?

Spin Half Particle

- $S_z = +1/2$ is a physical state
  - Ray in Hilbert space. Point on Bloch sphere
- $S_z = -1/2$ is negation of $S_z = +1/2$
  - Orthogonal ray. Antipode on Bloch sphere
- For any spin-half particle,
  - Either $S_z = +1/2$ or $S_z = -1/2$, not both
  - Stern-Gerlach measurement shows which is the case

- Nothing special about z. The x axis is just as good.
- For any spin-half particle,
  - Either $S_x = +1/2$ or $S_x = -1/2$, not both
  - Stern-Gerlach measurement shows which is the case

- $S_z = +1/2$ AND $S_x = +1/2$ is *meaningless*:
  - Hilbert space QM assigns it no meaning
    - No corresponding ray in the Hilbert space
  - No experiment which can measure it
    - Because it is not there!

Logic of Quantum Properties

- False statement is one whose negation is true
  - "Pennsylvania is a Canadian province"

- Meaningless statement: not formed according to rules governing proper use of the language
  - Example: "$P \wedge \vee Q$"
  - Negation of meaningless statement is meaningless

- Classical physical system:
  - Meaningful to combine two properties with AND
  - "The position is…" AND "The momentum is…"

- Quantum physical system:
  - Use AND only with *compatible* properties
  - Compatible: projectors commute: $PQ = QP$
  - $S_z = +1/2$, $S_x = +1/2$ are *incompatible*

Quantum Logic

- George Birkhoff and John von Neumann, Ann. Math. 37 (1936) 823, "The Logic of Quantum Mechanics"
  - $S_z = +1/2$ AND $S_x = +1/2$ is *meaningful, false*
  - Must modify rules of logic:

$$A \vee (B \wedge C) \neq (A \vee B) \wedge (A \vee C)$$
$$A \wedge (B \vee C) \neq (A \wedge B) \vee (A \wedge C)$$

- Consistent histories recognizes logical problem
  - But solves it in a different way
  - $S_z = +1/2$ AND $S_x = +1/2$ is *meaningless*

- Rules of logic remain unchanged, but one must
  - Recognize and exclude meaningless statements

- Single framework rule:
  - Meaningful quantum descriptions use a *single collection* of mutually compatible properties
  - Incompatible descriptions cannot be combined!

- Spin half
  - Can discuss S_z, which is $+1/2$ or $-1/2$
  - Can discuss S_x, which is $+1/2$ or $-1/2$
  - Cannot *combine* these discussions
    - Doing so makes no sense in Hilbert space QM

Probabilities I

- Standard (textbook) probability theory: $(\mathcal{S}, \mathcal{E}, \Pr)$
- Sample space $\mathcal{S}$ of *mutually-exclusive possibilities*
  - One and only one occurs in a given experiment
  - Examples:

  – $\{H, T\}$ for coin toss

  – $\{1, 2, 3, 4, 5, 6\}$ for roll of die
- Event algebra $\mathcal{E}$.
  - Assume $\mathcal{S}$ discrete; $\mathcal{E}$ = all subsets of $\mathcal{S}$
- Probability distribution Pr
  - To each s_i in $\mathcal{S}$ assign $p_i = \Pr(s_i) \geq 0$; $\sum_i p_i = 1$.

- Quantum mechanics: three options for probabilities

(i) Use standard theory; (ii) Invent new one;
(iii) Become confused (very popular option)

- Consistent histories uses *standard* probability theory
  - There are two tasks:

  – Define quantum sample space $\mathcal{S}$

  – Introduce probabilities Pr

Probabilities II

- Example of spin half
- $S_z = +1/2,\ -1/2$ are mutually exclusive possibilities
  - If one is true, the other is false
  - One, only one occurs in Stern-Gerlach experiment
  - They constitute the S_z sample space
- Likewise, $S_x = +1/2,\ -1/2$ constitute S_x sample space
- S_z and S_x sample spaces are *incompatible*
  - Events cannot be combined
  - Probabilistic inference cannot be combined
- WARNING!
  - *Incompatible* is a *quantum* concept
  - *Mutually Exclusive* is classical or quantum
  - Do not confuse the two!

Probabilities III

- General structure of quantum sample spaces

- Decomposition of the identity in projectors $\{P^j\}$
  – (Superscript is label, not power)
  - ∘ $P^j = (P^j)^\dagger, \quad P^j P^k = \delta_{jk} P^j, \quad I = \sum_j P^j$
  - ∘ Each $P^j \leftrightarrow$ physical property (Hilbert subspace)
  - ∘ $j \neq k \Rightarrow P^j P^k = 0$: mutually exclusive properties
  - ∘ $\sum_j P^j = 1$: at least one property is true.

- Event algebra $\mathcal{E}$ consists of all projectors of type
  $P = \sum_j \pi_j P^j, \quad \pi_j = 0 \text{ or } 1$

- Example: Orthonormal basis $\{|\phi^j\rangle\}$; $P^j = |\phi^j\rangle\langle\phi^j|$.

- S_z sample space for spin half: $I = [z^+] + [z^-]$
  - ∘ Use $[\psi]$ as abbreviation for dyad $|\psi\rangle\langle\psi|$.

- Before discussing quantum probabilities, make sure sample space exists! Many quantum paradoxes and other confusion can be traced to nonexistent sample spaces!

Born Rule I

- Time development of *closed* or *isolated* physical system
  - Open system: make it part of larger closed system
  - Use Schrödinger Eqn to compute probabilities
  - Born rule is first (but not last!) step

- Unitary time development operator $T(t, t')$
  - Comes from solving Schrödinger's equation
  - Time-independent H: $T(t, t') = e^{-i(t-t')H/\hbar}$

- Assume $|\psi_0\rangle$ at t_0
  - Sample space $\mathcal{S}$: basis $\{|\phi_1^k\rangle\}$ at t_1

- Born probabilities:

$$\Pr(\phi_1^k) = \Pr(\phi_1^k \,|\, \psi_0) = |\langle\phi_1^k|T(t_1, t_0)|\psi_0\rangle|^2$$

- $\Pr(\phi_1^k)$ = prob of $[\phi_1^k]$, *not measurement* of ϕ_1^k.
  - Good measurements reveal pre-existing properties.
  - Use *quantum* description *including* apparatus to discuss measurements

Born Rule II

- Born probabilities *depend on basis* $\{|\phi_1^k\rangle\}$
- Example. Spin half, $|\psi_0\rangle = |z^+\rangle$, $H = 0$, $T(t, t') = I$
- S_z basis $\{|z^+\rangle, |z^-\rangle\}$ at t_1:
  - ∘ $\Pr(z_1^+) = 1, \quad \Pr(z_1^-) = 0$
  - ∘ Subscript 1 indicates time t_1.
- S_x basis $\{|x^+\rangle, |x^-\rangle\}$ at t_1:
  - ∘ $\Pr(x_1^+) = 1/2 = \Pr(x_1^-)$
- Probabilities refer to properties of particle!
  - ∘ Bases incompatible; *cannot* assign probability to $S_z = +1/2$ AND $S_x = -1/2$ at time t_1
- "Gyroscope with axis in z direction" is misleading

∘ $S_z = +1/2$ at t_0, $S_x = -1/2$ at t_1 does *not* mean change in direction of axis!

∘ Better picture: gyroscope axis in random direction

∘ Given z component at t_0, what is probability of x component at t_1?

Pre-Probability $|\psi_t\rangle$

- Born probability

$$\Pr(\phi_1^k) = \Pr(\phi_1^k \,|\, \psi_0) = |\langle\phi_1^k|T(t_1,t_0)|\psi_0\rangle|^2$$

can be calculated in different ways.

- 1. Integrate Schrödinger Eqn from t_0 to t_1
  - $|\psi_1\rangle = T(t_1,t_0)|\psi_0\rangle$
  - $\Pr(\phi_1^k \,|\, \psi_0) = |\langle\phi_1^k|\psi_1\rangle|^2$

- 2. Integrate Schrödinger Eqn from t_1 to t_0
  - $|\phi_0^k\rangle = T(t_0,t_1)|\phi_1^k\rangle$
  - $\Pr(\phi_1^k \,|\, \psi_0) = |\langle\phi_0^k|\psi_0\rangle|^2$

- Approaches 1 and 2 equally good
  - Compare E&M: same result using different gauge

- Physical reality: $|\psi_0\rangle$ and the $\{|\phi_1^k\rangle\}$;
  however, $|\psi_1\rangle$ and $\{|\phi_0^k\rangle\}$ are *pre-probabilities*:
  tools for computing probabilities, *not* physical reality!

- "Wave function of universe" $|\psi_t\rangle = T(t,t_0)|\psi_0\rangle$
  - Everett: $|\psi_t\rangle$ represents physical reality
  - Histories: $|\psi_t\rangle$ is pre-probability: useful for finding Born probabilities; inadequate for others

Histories

- Samples space $\mathcal{S}$ for classical stochastic process
  - Sequence of events
  - Example: coin tossed three times:

  HTH, HTT, HHT, ... are all different
  - *One and only one* sequence in given experiment

- Other stochastic processes:
  - Random walk
  - Brownian motion
  - Waterloo weather

- Quantum sequence of events for Hilbert space $\mathcal{H}$

$$Y = F_0 \odot F_1 \odot \cdots F_f$$

  - F_j projector on ray/subspace of $\mathcal{H}$
  - "F_0 at t_0, F_1 at t_1, ..."
  - Different F_j *not* (necessarily) related by Schr Eqn
  - Call such a sequence a *history*

- Technical comments:
  - $\odot$ is a modification of $\otimes$
  - History Y an element of $\mathcal{H} \odot \mathcal{H} \odot \cdots \mathcal{H}$.

Families of Histories

- Quantum sample space $\mathcal{S} = \{Y^\alpha\}$ consists of histories
- Simplest interesting situation:
  - ∘ Single initial state $[\psi_0] = |\psi_0\rangle\langle\psi_0|$ at t_0
  - ∘ $t_j > t_0$: $I = \sum_{\alpha_j} P_j^{\alpha_j}$
- Histories indexed by $\alpha = (\alpha_1, \alpha_2 \ldots)$
  $Y^\alpha = [\psi_0] \odot P_1^{\alpha_1} \odot P_2^{\alpha_2} \odot \cdots$
- *One and only one* history from $\mathcal{S} = \{Y^\alpha\}$ actually occurs in quantum system starting in $[\psi_0]$ at t_0.
  - ∘ Projectors $P_j^{\alpha_j}$ not related by Schr eqn
- QM does not say *which* history occurs
  - ∘ QM can assign probabilities

Probabilities for Histories

- Use isolated/closed system
  - Open systems more complicated
  - Any apparatus is *part* of quantum system
  – in contrast with textbook approach

- Born rule limited to 2-time histories, $t_0 < t_1$
  - New rule needed for 3 or more times
  - Quantum probabilities (usually) not Markovian

- Histories approach *only* assigns probabilities to *consistent* families
  - For consistent families these probabilities
  – make physical sense
  – agree with Born for two times

- Consistency conditions: Chs. 10, 11 of *Consistent Quantum Theory*

Consistency Conditions

- Simplest case: pure initial state $|\psi_0\rangle$, chain kets; see *Consistent Quantum Theory*, Sec. 11.6
- Recursively define

$$
\begin{aligned}
|\alpha_1\rangle &= P^{\alpha_1} T(t_1, t_0)|\psi_0\rangle, \\
|\alpha_1, \alpha_2\rangle &= P^{\alpha_2} T(t_2, t_1)|\alpha_1\rangle, \\
|\alpha_1, \alpha_2, \alpha_3\rangle &= P^{\alpha_3} T(t_3, t_2)|\alpha_1, \alpha_2\rangle
\end{aligned}
$$

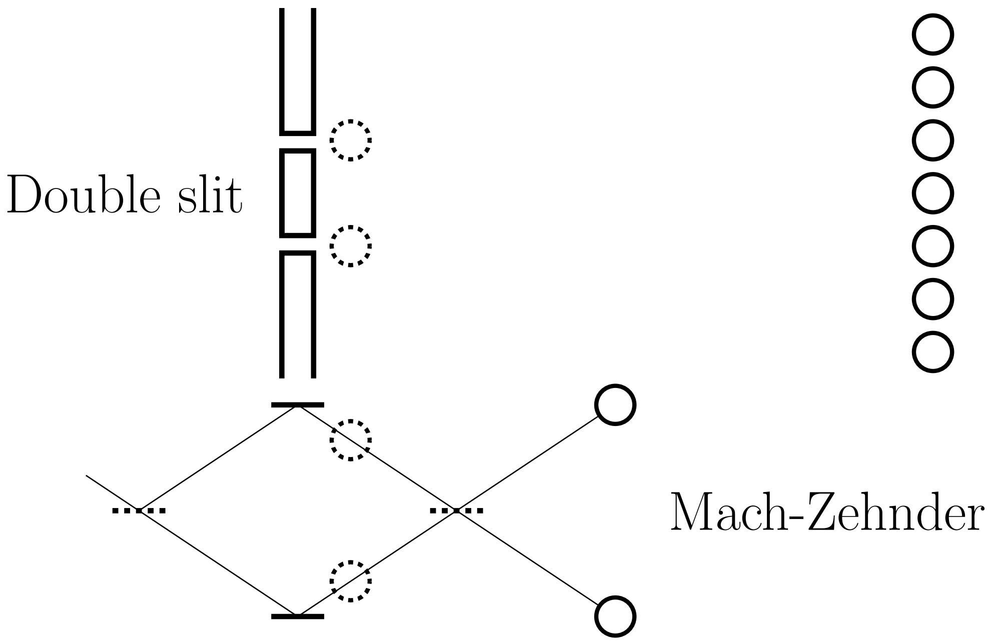
and so forth

- Require orthogonality at each stage:

$$
\begin{gathered}
\alpha_1 \neq \alpha_1' \Rightarrow \langle\alpha_1|\alpha_1'\rangle = 0, \\
\alpha_1 \neq \alpha_1' \text{ OR } \alpha_2 \neq \alpha_2' \Rightarrow \langle\alpha_1, \alpha_2|\alpha_1', \alpha_2'\rangle = 0, \\
\text{Etc.}
\end{gathered}
$$

- $\Pr\left(Y^{(\alpha_1,\alpha_2,\ldots)}\right) = \langle\alpha_1, \ldots \alpha_f|\alpha_1, \ldots \alpha_f\rangle$.
- $\{P_1^{\alpha_1}\}$ orthogonal *implies*: $\alpha_1 \neq \alpha_1' \Rightarrow \langle\alpha_1|\alpha_1'\rangle = 0$
  - Two-time $t_0 < t_1$ histories automatically consistent
  - Born rule always works
- Consistency not trivial for 3 or more times.

Double Slit + Mach-Zehnder

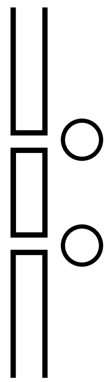


- Correspondences:
  - Which slit? ↔ Which arm?
  - Detectors behind slits ↔ inside interferometer
  - In interference zone ↔ following 2d beam splitter
- For precise description, use Mach-Zehnder
  - Basic idea applies to double slit

No Detectors

- Family "Super" (superposition)
  - ∘ Initial wave $|\psi_0\rangle$ arrives at slits
  - – Ignore reflection (Mach-Zehnder better for this)
  - ∘ Passes through slits in *coherent superposition*
- Family "Which" (which slit?)
  - ∘ Same $|\psi_0\rangle$
  - ∘ Particle passes through definite slit
- Either family gives *valid quantum description*
  - ∘ Physicist can choose either. Liberté !
  - ∘ Spin 1/2 analogy: Use *either* S_z *or* S_x basis
- Both families equally "fundamental" QM: Egalité !
- Cannot combine Super with Which: Incompatibilité !

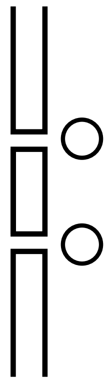
Detectors Behind Slits I



- Detectors are quantum objects!
  - Hilbert space includes detectors
  - Histories include projectors on detector states
  - "Pointer basis": Macroscopically distinct detector states for decomposition of identity

- Histories: $[\Psi_0] \odot$ Particle $\odot$ Detector
  - Initial $|\Psi_0\rangle = |\psi\rangle \otimes |\text{Detectors Ready}\rangle$
  - Particle: Super(position) OR Which (slit) basis
  - Detector: Point(er) basis OR Scat (Schr. cat) basis

Detectors Behind Slits II



Family:	Particle:	Detector:	Consistent?
1. Unitary	Super	Scat	Yes
2. Textbook	Super	Point	Yes
3. Exptlist	Which	Point	Yes
4. Nonsense	Which	Scat	No

- Families 1, 2, 3 equally good quantum descriptions!

  1. Individual detectors cannot be discussed.
     Misleading concept of "dead and live" cat
  2. "Which slit?" is meaningless question for this family
  3. Experimentalist description: Particle came through slit preceding triggered detector

- Family 4 unacceptable: violates consistency conditions

Detectors in Interference Region

Family:	Particle:	Detector:	Consistent?
1. Unitary	Super	Scat	Yes
2. Textbook	Super	Point	Yes
3. DefinSlit	Which	Scat*	Yes
4. Nonsense	Which	Point	No

- Families 1, 2, 3 equally good quantum descriptions!
  1. Individual detectors cannot be discussed
  2. "Which slit?" is meaningless question
  3. Scat* differs from Scat, but equally odd
- Family 4 unacceptable: violates consistency conditions

Delayed Choice

- Detectors behind slits removed at last moment
  - Does the future influence the past?

- Consistent families in the two cases:

Family:	Particle:	Near Detectors:	Far Detectors:
1. Unitary	Super	Scat	
2. Textbook	Super	Point	
3. Exptlist	Which	Point	
4. Unitary	Super		Scat
5. Textbook	Super		Point
6. DefinSlit	Which		Scat*

- Future influences past = misunderstanding
  - Many *equally valid* quantum descriptions
  - Choosing one does not influence reality; it determines which questions have answers

Einstein Podolsky Rosen

- Phys. Rev. 1935 "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"
  - Their answer: No

- Bohm 1952. Particles a and b far apart in spin singlet
  - $|\psi_0\rangle = \left(|z_a^+ z_b^-\rangle - |z_a^- z_b^+\rangle\right)/\sqrt{2}$
  - A measures S_{az}, gets result $+1/2$ or $-1/2$
    Conclusion $S_{bz} = -S_{az}$
  - A could measure S_{ax}, get result $+1/2$ or $-1/2$
    Conclusion $S_{bx} = -S_{ax}$

- EPR objection, stated in Bohm language
  - Measurement of a cannot affect b, so
  - S_{bz} values same *before and after* A measurement
  - A could just as well measure S_{ax}
  - Both S_{bz}, S_{bx} have definite values regardless of what is measured
  - QM is incomplete: Hilbert space is too small!

Nonlocality

- Claim: EPR ⇒ QM nonlocal!
    - A's measurement of particle a has an Instantaneous Nonlocal Superluminal (INS) influence on particle b
    - Idea supposedly supported by Bell inequalities
- Laborious analysis proves that
    - INS influences carry no information!
- Histories response:
    - INS influences carry no information — because they do not exist!
    - Bell ineq. violations ⇒ hidden variables don't work
    - Hilbert space QM, properly understood, is *local*

Classical Analogy

- Two colored slips of paper: R(ed), G(reen)
- Pete in Pittsburgh
  - Seals them in opague envelopes
  - Shuffles envelopes
  - Addresses one to Alice in Atlanta
  - The other to Bob and Boston
- Alice opens her envelope, sees G
  - Conclusion: Bob's envelope contains R
- Does this indicate INS influence of Alice's action on Bob's envelope?
  - Perhaps there is some simpler explanation

EPR Correlations

- Histories with initial $|\psi_0\rangle = \left(|z_a^+ z_b^-\rangle - |z_a^- z_b^+\rangle\right)/\sqrt{2}$
  - No measurements (until later)

- Unitary family $[\psi_0] \odot [\psi_0] \odot [\psi_0] \odot \cdots$
  - Consistent, probability 1
  - Incompatible with individual properties of a, b
  - Must consider $|\psi\rangle$ pre-probability in order to use reduced density operators ρ_a, ρ_b

- Family using S_z bases: $[\psi_0] \odot \begin{cases} z_a^+ z_b^- \\ z_a^- z_b^+ \end{cases}$
  - Perfect correlations with no measurements
  - Like R, G slips of paper inside envelopes
  - Good measurements will show what is there

- Family using S_x bases: $[\psi_0] \odot \begin{cases} x_a^+ x_b^- \\ x_a^- x_b^+ \end{cases}$
  - Incompatible with previous family

- No magical INS influences thus far!
  - Will measurements bring them to light?

EPR Measurement Correlations

- Measuring apparatus Z_a for S_{az}
  - Initial state $|\Psi_0\rangle = |\psi_0\rangle \otimes |Z_a^0\rangle$
  - Pointer basis projectors Z_a^+, Z_a^-

- Unitary history → apparatus Schrödinger cat state
  - Good QM, but does not address our questions

- Family 1. $[\Psi_0] \odot \begin{cases} z_a^+ z_b^- \odot Z_a^+ \\ z_a^- z_b^+ \odot Z_a^- \end{cases}$
  - Apparatus $Z_a^\pm$ correlated with prior states of both particles
  - Good measurements show what is there

- Extensions of this family show that:
  - Z_a^+ outcome implies $S_{bz} = -1/2$ for particle b *before, during* and *after* measurement
  - No sign of INS influence!

EPR Delayed Choice

- Measure S_{ax} instead of S_{az}
  - ∘ Use $|\Psi_0\rangle = |\psi_0\rangle \otimes |X_a^0\rangle$
  - ∘ Or use quantum coin to replace Z_a with X_a
  - – Possibly at the last moment

- Family 2. $[\Psi_0] \odot \begin{cases} x_a^+ x_b^- \odot X_a^+ \odot x_b^- \\ x_a^- x_b^+ \odot X_a^- \odot x_b^+ \end{cases}$

  ∘ Outcome X_a^+ correlated with x_b^- — both before and after measurement

- Family 3. $[\Psi_0] \odot \begin{cases} z_b^+ \odot \{X_a^+, X_a^-\} \odot z_b^+ \\ z_b^- \odot \{X_a^+, X_a^-\} \odot z_b^- \end{cases}$

  ∘ Can discuss S_{bz} when S_{ax} measured, why not?

  ∘ S_{bz} for particle b *exactly the same* before and after measurement on particle a

  ∘ Demonstration of *absence* of INS influences!

Is QM Complete?

- Quantum description of physical reality *available in 1935* was *incomplete* because it:
  - Lacked consistent probabilities
  - Limited set of stochastic descriptions
  - Misleading reliance on "measurement"
  - Lacked good description of measurement apparatus
  - Wavefunction "collapse" not well formulated
- Einstein, Podolsky, Rosen correct in raising objections
- Quantum description *available in 2005* has
  - Consistent system of probabilities for microsystems
  - Broad class of stochastic descriptions
  - Formulation does not rely on measurement
  - Same principles for measurements, other processes
  - Conditional probabilities replace "collapse"
- Is it now complete?

Discussion Topics

- Liberty in choosing alternative descriptions
  - Analogy of ordinary historian
  - Approach does not lead to contradictions

- Measurements
  - Reveal pre-existing properties

  – if included in framework

- Von Neumann measurements
  - Very special type
  - Usual interpretation is not wrong

  – but it is misleading

- Approximate consistency: Dowker and Kent

- Consistent histories vs. Everett
  - $|\psi_t\rangle$: pre-probability, not reality

- Consistent histories vs. Bohm
  - Particle triggers detector by not passing through it