Teaching and Learning with a Quantum Network Simulator

A Cross-Disciplinary Module

Physics · Engineering · Economics · Policy
Public Health · Community Engagement

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Module Description

The Quantum Network Simulator is an open, algebra-based planning tool anchored to the Qunnect/Cisco GothamQ metro demonstration (February 18, 2026), which operated over deployed commercial fiber and validated high-speed entanglement swapping with an integrated hardware–software networking stack. **The simulator is designed for learning and planning, not hype:** it turns a real demonstration into a transparent, auditable model that students can interrogate, modify, and defend.

Rather than treating "quantum networking" as a mysterious capability, the notebook makes the engineering tradeoffs explicit. **It is not a black box:** every output number is computed from a stated equation; every equation encodes a physical constraint (loss, timing, memory coherence, heralding); and every constraint maps to a concrete system-level decision (node spacing, corridor cost, service targets, and the current technology bottleneck).

The module is structured in three layers, each accessible at a different level of technical preparation:

- **Cell 1 — Physics engine.** Parameterized model: fiber loss, heralding latency, entanglement rate, fidelity decay, repeater chain. Requires: algebra, exponential functions, basic probability.
- **Cell 2 — Interactive planning UI.** Dial corridor length, area, and service targets $\rightarrow$ live node count, CapEx estimate, and binding constraint (Qunnect or Cisco bottleneck). Requires: no equations — interpretation only.
- **Cell 3 — Figures.** Seven publication-ready plots for discussion, presentation, and policy analysis. Requires: graph literacy.

Across these layers, learners practice the same transferable workflow: (1) state assumptions, (2) propagate them quantitatively, (3) identify the binding constraint, and (4) communicate tradeoffs to a technical or non-technical stakeholder. This supports cross-disciplinary instruction where physics students own the model, policy students own the objective and constraints, and workforce/community students own deployment realism and communication.

> **Entry points by preparation level:** High school (algebra, geography) $\rightarrow$ Cell 2 + Cell 3. Undergraduate STEM $\rightarrow$ All three cells. Graduate / professional $\rightarrow$ Full model with parameter substitution and sensitivity analysis. Policy / economics / public health $\rightarrow$ Cell 2 + deployment table + discussion questions below.

Cross-Disciplinary Learning Dimensions

Physics and Engineering

The simulator makes abstract quantum concepts measurable. Students observe how fidelity decays exponentially with memory time, why the 41.6 km repeater segment is not arbitrary (derived from hardware (F_{min} and T_{mem}, and fiber speed), and how technology constraint transitions from quantum memory to fiber loss as technology improves.

Key concepts: Beer-Lambert attenuation, exponential decay, renewal processes, fidelity, quantum memory coherence, BSM.

Exercise: Replace $\tau_{\text{orch}} = 5\,\mu$s with a measured value. How does 41.6 km change? Who owns the gap?

Economics and Policy

The deployment table introduces **marginal cost per constituent** as a policy metric. Students sort counties by people-per-dollar, observe the diminishing returns curve, and must defend a phased investment strategy to a skeptical appropriations committee.

Key concepts: marginal vs. average cost, infrastructure externalities, public goods, phased investment, CapEx vs. OpEx.

Discussion: Phase 1 connects 63% of NM for \$20M. Phase 3 (rural) requires \$47M for 8.6% of the population. Argue for Phase 3. What does the model omit?

Public Health and Data Security

Harvest-now-decrypt-later is a public health problem. Health records generated today have a privacy lifetime of decades. Students examine the gap between HIPAA compliance (a legal requirement) and physics-guaranteed security.

Case study: UNM Health transmits HIPAA data on classical TLS fiber today. Map the vulnerability. Which nodes in the deployment table close it? What is the cost and timeline?

Community Engagement and Workforce

Each repeater node requires installation and maintenance — providing jobs for which a two-year technician training can be sufficient. Students connect infrastructure to local employment, examine what buy-in means in a rural or indigenous community, and design outreach for a specific county.

Design exercise: Introduce the quantum network technician program in McKinley County. The word "quantum" may not translate. Write a one-page community brief in terms the community uses.

What Students Produce

- A corridor analysis for a region of their choice — repeater count, CapEx, people connected, binding constraint
- A people-per-dollar deployment table for their state or country, sorted by population impact
- A one-page policy brief arguing for or against a specific phase of the NM deployment, with quantified tradeoffs
- A sensitivity analysis: how does the deployment plan change if T_{mem} reaches 1 ms two years earlier than projected?
- A community outreach document for a specific rural county or indigenous nation, explaining the technology in local terms
- A vendor accountability memo: at the current operating point, which parameter — memory time or fiber loss — limits performance, and which company owns the fix?

Why This Module

Most quantum education follows one of two paths: highly technical (inaccessible without advanced physics) or superficially motivational (no quantitative content, no accountability).

In contrast, this module is grounded in a real, verified demonstration on live commercial fiber — not a thought experiment. The physics is simplified but not wrong: every approximation is labeled, every parameter is cited, and the model's limitations are explicit. Students engage with genuine uncertainty (the estimated τ_{orch}) and are asked to say what would change if the uncertainty were resolved.

> **The transferable skill is not quantum mechanics.** It is the ability to connect a physical constraint to a procurement decision, a procurement decision to a deployment plan, a deployment plan to a workforce requirement, and a workforce requirement to a community outcome. That reasoning chain is the same whether the infrastructure is quantum networking, renewable energy, rural broadband, or public health.

Module at a Glance

Audience	Entry cell	Core skill	Signature deliverable
HS physics / math	Cell 2 + figures	Graph interpretation	Corridor comparison: NM vs. home state
Undergrad STEM	All cells	Model derivation	Sensitivity analysis with parameter swap
Undergrad policy	Cell 2 + table	Marginal cost analysis	Phased investment brief to legislature
Public health	Cell 2 + redbox	Threat surface mapping	UNM Health vulnerability + cost to close
Community college	Cell 2	Workforce planning	Job pipeline estimate for two counties
Graduate / SA	Full model	Bottleneck diagnosis	Vendor accountability memo

> **Instructor note:** The simulator is a Jupyter notebook (Python, no special quantum libraries required beyond NumPy and Matplotlib). All figures are reproducible from the notebook. The deployment table is generated from 2020 Census county data and the physics engine — students can substitute any US state or international region by replacing the county input file. The module is designed to be taught in a single 3-hour workshop or spread across a semester as recurring quantitative case studies.

The simulator is anchored to the Qunnect/Cisco GothamQ metro demonstration (February 18, 2026) on deployed commercial fiber and to published quantum networking literature (Sangouard et al., Rev. Mod. Phys. 83, 2011; Wang et al., arXiv:2503.11564, 2025; PRX Quantum 5, 030330, 2024). All parameters are cited; all approximations are labeled.

Answer Key

Instructor Reference — Not for Student Distribution

> **Note to instructors:** Most prompts in this module are open-ended by design — they train reasoning chains, not recall. The answers below provide the *minimum defensible response* and flag the key moves a strong answer must make. Student responses that go further, challenge assumptions, or identify model omissions should be rewarded.

Physics & Engineering Exercise

Prompt: Replace $\tau_{\text{orch}} = 5\,\mu$s with a measured value. How does 41.6 km change? Who owns the gap?

Key Concepts to Unlock First

The 41.6 km segment length is *not* chosen for geography — it is the maximum fiber distance light can travel during one orchestration cycle before fidelity falls below the usable threshold F_{min}. The governing relation is:

$$L_{\text{seg}} = \frac{v_f \cdot T_{\text{mem}}}{n_{\text{rounds}}} \quad \text{where} \quad v_f = \frac{c}{n_{\text{fiber}}} \approx 2.0 \times 10^5 \text{ km/s}$$

With $\tau_{\text{orch}} = 5\,\mu$s and a single heralding round, $L_{\text{seg}} \approx 2.0 \times 10^5 \times 5 \times 10^{-6} = 1.0$ km per round-trip half, scaling to ∼41.6 km under the full model timing budget (including BSM latency and memory hold time).

What Changes When τ_{orch} Changes

- **If τ_{orch} decreases** (faster orchestration electronics): L_{seg} shrinks; more repeater nodes are required for the same corridor; CapEx rises. Quantum Network Providers must supply faster heralding logic or reduce memory hold requirements.
- **If τ_{orch} increases** (slower, or if measured $> 5\,\mu$s): L_{seg} grows; fewer nodes needed; CapEx drops. However, longer hold times stress quantum memory coherence (T_2), so fidelity may drop below F_{min} before the gain is realized — the two parameters compete.
- **Who owns the gap:** Orchestration latency (τ_{orch}) is primarily a **Quantum Network Provider** responsibility — it lives in the heralding and control electronics of the quantum memory node. Fiber propagation loss at each segment is a carrier responsibility. A strong answer identifies both owners and notes that the 41.6 km figure encodes a *negotiated* boundary between them.

Grading Rubric

1. Correctly identifies L_{seg} as timing-derived, not geography-derived. *(2 pts)*
2. States direction of change in node count when τ_{orch} changes. *(2 pts)*
3. Identifies Qunnect as owner of orchestration latency. *(2 pts)*
4. Recognizes the T_2–τ_{orch} tension (fidelity vs. segment length). *(2 pts)*
5. Bonus: quantifies the new L_{seg} for a student-chosen τ_{orch} value. *(2 pts)*

Economics & Policy Discussion

Prompt: Phase 1 connects 63% of NM for $20M. Phase 3 (rural) requires $47M for 8.6% of the population. Argue for Phase 3. What does the model omit?

Minimum Defensible Argument for Phase 3

A strong Phase 3 argument must reframe the metric. **Cost-per-person is the wrong denominator** when the served population is structurally excluded from existing secure infrastructure. Key moves:

1. **Externality argument.** Rural and tribal communities in NM already lack fiber parity. Quantum-secured links deliver a *leapfrog* benefit unavailable at any price on classical infrastructure. The counterfactual cost is not $0 — it is the ongoing cost of insecure health, legal, and government data transmission over decades.
2. **Federal leverage.** Phase 3 corridors likely qualify for BEAD, IRA, and tribal broadband funding. The $47M state figure may fall to $10–15M after federal co-investment — changing the marginal cost calculation substantially.
3. **Workforce multiplier.** Rural nodes require local technicians. Phase 3 generates proportionally *more* jobs per dollar in high-unemployment counties (McKinley, Cibola, Catron) than urban Phase 1 nodes, where labor markets are tighter.
4. **Sovereignty and trust.** For tribal nations, secure communication infrastructure is a governance and sovereignty

issue, not merely a connectivity metric. Omitting this makes the model systematically undervalue Phase 3.

What the Model Omits (Required)

- **OpEx.** CapEx figures exclude ongoing maintenance, power, and staffing. Rural nodes have higher OpEx per node due to distance and workforce scarcity.
- **Demand elasticity.** The model assumes fixed service targets. It does not model how usage (and therefore value) grows once the network exists — a standard infrastructure externality.
- **Political economy.** Phased investments are vulnerable to cancellation between phases. Phase 3 may never arrive if it is not committed to in Phase 1 appropriations.
- **Non-monetary benefits.** Health outcome improvements from secure telemedicine, legal services access, and reduced data-breach liability are not in the CapEx model.

Grading Rubric

1. Reframes cost-per-person with at least one alternative metric. *(2 pts)*
2. Identifies at least one federal co-funding mechanism by name. *(2 pts)*
3. Identifies at least two model omissions. *(2 pts)*
4. Addresses the sovereignty / trust dimension (tribal nations). *(2 pts)*
5. Bonus: provides a revised cost estimate incorporating federal co-investment. *(2 pts)*

Public Health & Data Security Case Study

Prompt: UNM Health transmits HIPAA data on classical TLS fiber today. Map the vulnerability. Which nodes close it? What is the cost and timeline?

Vulnerability Map

1. **Harvest-now-decrypt-later (HNDL).** An adversary intercepting today's TLS-encrypted traffic can store ciphertext and decrypt it once a cryptographically-relevant quantum computer (CRQC) exists — estimated 10–15 years (NIST, 2024). Medical records have a privacy lifetime of 20–50 years. The vulnerability window is *already open*.
2. **HIPAA is a legal requirement, not a security contract.** HIPAA requires "reasonable and appropriate" safeguards — a compliance standard written before HNDL was a practical threat. Meeting HIPAA today does not close the HNDL gap.
3. **TLS key exchange is the attack surface.** RSA and ECDH key exchanges (used in TLS 1.3) are vulnerable to Shor's algorithm. The symmetric payload encryption (AES-256) is not broken by known quantum algorithms, but requires an uncompromised session key.

Which Nodes Close the Vulnerability

The deployment table nodes serving Bernalillo County (Albuquerque / UNM Health campus) close the local last-mile vulnerability. A complete solution requires:

- **UNM Health ↔ State DOH link:** Bernalillo–Santa Fe corridor nodes (Phase 1, ∼$3–5M allocated segment).
- **UNM Health ↔ rural clinics:** Phase 2/3 nodes extending to Sandoval, Torrance, and Valencia counties.
- **QKD integration at the endpoint:** Nodes alone are insufficient — UNM Health should transition to QKD-capable endpoints and retire RSA/ECDH at the application layer.

Cost and Timeline

Action	Est. cost	Timeline	Dependency
Phase 1 corridor nodes	$20M (state)	2–3 years	Legislative appropriation
QKD endpoint hardware	$0.5–2M	1–2 years	Depends on product availability
HIPAA policy update	$0	6 months	HHS guidance update
Staff training	$0.1–0.3M	Ongoing	Workforce program

Grading Rubric

1. Correctly defines HNDL and its relevance to medical records. *(2 pts)*
2. Distinguishes HIPAA compliance from physics-guaranteed security. *(2 pts)*
3. Identifies the TLS key-exchange (not payload) as the attack surface. *(2 pts)*
4. Names specific deployment-table nodes that close the gap. *(2 pts)*

5. Bonus: estimates total cost to close the gap and states limiting assumption. *(2 pts)*

Community Engagement Design Exercise

Prompt: Introduce the quantum network technician program in McKinley County. The word "quantum" may not translate. Write a one-page brief in terms the community uses.

What a Strong Brief Must Do

This exercise has no single correct answer. It is graded on communicative appropriateness, not technical accuracy. Evaluate on five criteria:

1. **Leads with community benefit, not technology.** Opens with jobs, health data protection, or reliable communication — not with physics.
2. **Avoids or translates jargon.** "Quantum" $\to$ e.g., "a new kind of communication signal that cannot be secretly copied." "Entanglement" $\to$ e.g., "a paired signal: if someone touches one end, the other end knows immediately." "Fiber" is acceptable (already in use regionally). "Repeater" $\to$ "signal relay station" or equivalent.
3. **Specifies McKinley County context.** References Gallup, Navajo Nation, and/or the specific industries (healthcare, government, education) whose data security is at stake. Generic language is penalized.
4. **States a concrete ask or next step.** Community briefs without a call to action are incomplete. Examples: attend an information session, contact a tribal liaison, apply to a technician training cohort.
5. **Appropriate register.** Written at an accessible level (aim for grade 8–10 reading level). Avoids condescension. Acknowledges that the community has expertise the technology team does not (land, relationships, local logistics).

> **Sample opening sentence (illustrative, not prescriptive):** "A new infrastructure project will bring high-paying, locally-based maintenance jobs to McKinley County — and the equipment it maintains will protect the privacy of medical and legal records in a way that current internet technology cannot guarantee."

Common Errors to Flag

- Leading with the physics demonstration (GothamQ / Manhattan) — irrelevant to audience.
- Using "quantum-secure" or "physics-guaranteed" without translation.
- Omitting any mention of the Navajo Nation or tribal governance context.
- Treating McKinley County as simply "rural" rather than as a specific place with specific infrastructure history and political relationships.

Sensitivity Analysis

Prompt: How does the deployment plan change if T_{mem} reaches 1 ms two years earlier than projected?

Model Mechanics

T_{mem} (memory coherence time) sets the maximum useful hold time per heralding attempt. Longer T_{mem} allows:

- Longer L_{seg} (fewer repeater nodes per corridor).
- Higher entanglement rate (more heralding attempts per memory window).
- Relaxed timing requirements on τ_{orch}.

Quantitative Direction

At the baseline ($T_{\text{mem}} \sim 0.1$ ms), node spacing is ≈ 41.6 km. Scaling to $T_{\text{mem}} = 1$ ms (10$\times$ improvement) allows node spacing to grow roughly as $\sqrt{T_{\text{mem}}}$ (dominated by the fidelity decay envelope), yielding $L_{\text{seg}} \approx 130$ km. A 500 km corridor drops from ~12 nodes to ~4 nodes. CapEx falls by roughly 60–65% for node hardware; fiber trenching costs are unaffected (they are distance-dependent, not node-count-dependent).

Strategic Implications

1. **Phase schedule compression.** Fewer nodes means faster installation; Phase 2 and Phase 3 timelines may compress by 1–2 years.
2. **Technology constraint shift.** With quantum memory no longer limiting segment length, the constraint transitions to fiber loss.
3. **Rural economics improve.** Long-segment nodes are cheaper per km in low-density corridors. Phase 3 CapEx falls more than Phase 1 CapEx (urban corridors are short regardless of T_{mem}).
4. **Procurement risk.** If $T_{\text{mem}} = 1$ ms hardware is available two years early, contracts signed at baseline specifications may over-specify infrastructure. Strong answer flags the procurement lock-in risk.

Grading Rubric

1. Correctly states direction of L_{seg} change. *(2 pts)*
2. Quantifies approximate new node count for a specific corridor. *(2 pts)*
3. Identifies shift in binding constraint from Qunnect to Cisco. *(2 pts)*
4. Notes differential benefit for rural vs. urban corridors. *(2 pts)*
5. Bonus: identifies procurement lock-in risk. *(2 pts)*

Vendor Accountability Memo

Prompt: At the current operating point, which parameter — memory time or fiber loss — limits performance, and which company owns the fix?

Answer

At the **current operating point** the technology constraint is **quantum memory coherence time** (T_{mem}), owned by the Quantum Network Provider.

Reasoning chain a strong memo must trace:

1. The maximum useful segment length is set by the shorter of two limits: (a) the distance at which fiber attenuation reduces photon arrival probability below the heralding threshold, and (b) the distance light travels in one memory coherence window.
2. At current $T_{\text{mem}} \approx 0.1$ ms, the Qunnect limit yields $L_{\text{seg}} \approx 41.6$ km. At 0.2 dB/km fiber loss (Cisco SMF), the attenuation limit for a viable heralding probability is ≈ 80–100 km. The quantum memory limit is tighter; it sets the segment length.
3. **Therefore:** the Quantum Network Provider owns the fix. Improving T_{mem} from 0.1 ms to 1 ms would relax the technology constraint and transfer it to fiber loss.
4. The memo should specify what the Quantum Network Provider must deliver (target T_{mem}, timeline, verification method) and what milestone would trigger a re-evaluation of contracts.

> **Key sentence every strong memo includes:** "At the current operating point, memory coherence is the technology constraint. Fiber loss becomes binding only after T_{mem} exceeds approximately 0.5 ms. Until that threshold is crossed, additional investment in low-loss fiber does not improve end-to-end performance."

Grading Rubric

1. Correctly identifies T_{mem} as the current technology constraint. *(3 pts)*
2. Correctly attributes Quantum Network Provider as the responsible vendor. *(3 pts)*
3. States the approximate T_{mem} threshold at which constraint transfers to fiber loss. *(2 pts)*
4. Specifies a measurable deliverable the Quantum Network Provider must meet (target value + timeline). *(2 pts)*

Answer key prepared for instructor use in conjunction with the GothamQ Quantum Network Simulator (Sim 1). Parameters and model derivations follow Sangouard et al., Rev. Mod. Phys. 83, 2011 and the Sim 1 notebook documentation. Rubric point values are suggestions; rescale to your course's grading scheme.