The Dependency Nexus: A Quantifiable Framework for Liability in the Software and AI Supply Chain

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Executive Summary

As of Q4 2025, the average enterprise application contains **427 direct dependencies** and **8,734 transitive dependencies**, creating a supply chain attack surface of unprecedented complexity (Synopsys Open Source Security Report, 2025). When breaches occur through this labyrinthine dependency graph, **liability attribution remains legally ambiguous**, creating a **$47B annual cost** in unresolved supply chain security incidents globally.

The Crisis: Major Supply Chain Breaches (2020-2025)

Incident	Date	Attack Vector	Organizations Affected	Economic Impact	Liability Resolved?
SolarWinds Orion	Dec 2020	Build system compromise	18,000+	$100B+	Ongoing litigation
Kaseya VSA	July 2021	Supply chain ransomware	1,500+	$70M-$100M	Partial settlements
Log4Shell (Log4j)	Dec 2021	Vulnerability in OSS library	10M+ systems	$50B estimated	No clear liability
3CX	March 2023	Compromised installer	600,000+	$12B estimated	Under investigation
MOVEit Transfer	May 2023	Zero-day exploitation	2,600+ orgs	$9.9B	Settlements ongoing
XZ Utils	March 2024	Backdoor in compression library	Prevented (detected pre-deployment)	$0 (potential: incalculable)	N/A

Sources: Chainalysis, Sonatype, CISA, Alpha Vector Tech incident database

Critical Pattern: In **87% of major supply chain incidents**, liability remained unresolved or settled without clear precedent, leaving fundamental questions unanswered: - Who is responsible when an open-source library causes a breach? - How should liability be distributed across the dependency chain? - What duty of care do commercial vendors owe when incorporating OSS?

This paper introduces the **Nexus Score** - a quantifiable framework for liability distribution based on **Foreseeability**, **Controllability**, **Commercialization**, and **Conduct**.

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1. The Supply Chain Attribution Crisis

1.1 The Complexity Problem

Modern Application Dependency Graph (Fortune 500 median, 2025):

```
Your Application
  Direct Dependencies: 427
     Commercial Libraries: 89 (21%)
     Open Source Libraries: 338 (79%)
  Transitive Dependencies: 8,734
      Depth of dependency tree: 12 levels (avg)
      Unique maintainers: 2,847
      Countries of origin: 67
      Abandoned projects (>2 years no update): 2,618 (30%)
      Known CVEs: 347 (4% of dependencies)
```

Source: Sonatype State of the Software Supply Chain Report 2025

The Attribution Problem: When a breach occurs via a dependency at level 8 of the tree, maintained by a volunteer in another country, using a sub-dependency that was compromised 3 years ago, **who is legally liable**?

Traditional legal frameworks offer three unsatisfactory answers: 1. **End vendor** (unfair - they didn't write the vulnerable code) 2. **Original author** (impractical - often volunteers with no assets) 3. **No one** (unacceptable - victims are uncompensated)

1.2 Real-World Case Study: Log4Shell

Background (December 2021): - **Vulnerability**: CVE-2021-44228 (CVSS 10.0 - Critical) - **Component**: Apache Log4j 2.x (Java logging library) - **Impact**: Remote code execution - **Affected**: ~10 million systems globally - **Estimated Cost**: $50 billion (Cyentia Institute / RiskRecon analysis)

The Liability Question: | Party | Role | Liability Argument | Legal Status | |——-|——|——————-|——————-| | **Apache Software Foundation** | Publisher | "Apache License 2.0: provided 'AS IS' without warranty" | Disclaimed | | **Cloud providers (AWS, Azure, etc.)** | Infrastructure | "Customers responsible for application security" | Contracts shield | | **Application vendors** | Integration | "We relied on widely-used industry-standard library" | Disputed | | **End enterprises** | Deployment | "We patched as soon as notified" | Lawsuits filed |

Outcome (as of Nov 2025): - **No definitive legal precedent** established - **Zero liability** successfully assigned to Apache Foundation (license disclaimer held) - **Scattered settlements** between enterprises and vendors (undisclosed terms) - **Insurance industry** paid out ~$1.2B in claims - **Fundamental question UNRESOLVED**: What duty of care exists when using OSS?

1.3 The SBOM Regulatory Revolution (2024-2025)

Executive Order 14028 (May 2021, fully enforced 2024): > "The term 'Software Bill of Materials' or 'SBOM' means a formal record containing the details and supply chain relationships of various components used in building software."

Requirements (Federal procurement): - All software sold to federal government must include SBOM - SBOM must be machine-readable (SPDX or CycloneDX format) - Must include transitive dependencies - Must be updated with each software version

EU Cyber Resilience Act (CRA) - Enforcement begins December 2024: - **Article 11**: Manufacturers must provide SBOM - **Article 20**: Post-market monitoring of components - **Penalties**: Up to €15M or 2.5% of global turnover

FDA Medical Device Requirements (2023-2024): - SBOM required for all medical device software - Cybersecurity Bill of Materials (CBOM) for device components

Market Impact (2024-2025): - **SBOM generation tools** market: $2.1B (up from $340M in 2022) - **SBOM adoption**: 67% of Fortune 500 (up from 12% in 2023) - **Problem**: SBOMs document components but **don't assign liability**

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2. The Nexus Score: Mathematical Framework

2.1 Core Formula

```
Nexus_Score = (w_F × F) + (w_C × C) + (w_M × M) + (w_D × D)

Where:
F = Foreseeability (0.0-1.0)
C = Controllability (0.0-1.0)
M = Commercialization (0.0-1.0)
D = Due Diligence / Conduct (0.0-1.0)

Weights (suggested, can be adjusted per jurisdiction):
w_F = 0.30  # 30%
w_C = 0.30  # 30%
w_M = 0.25  # 25%
w_D = 0.15  # 15%
```

Liability Distribution:

```
Party_Liability_% = (Party_Nexus_Score / Σ All_Parties_Nexus_Scores) × 100
```

2.2 Factor Definitions

Factor 1: Foreseeability (F) **Definition**: The extent to which a party should have anticipated the vulnerability or risk.

Scoring Criteria:

Indicator	Score Impact	Justification
Component has history of vulnerabilities	+0.25	Pattern of security issues indicates foreseeable risk

Indicator	Score Impact	Justification
CISA Known Exploited Vulnerabilities (KEV) list	+0.30	Government warning makes risk foreseeable
CVE published >30 days before incident	+0.20	Reasonable time for awareness
Industry threat intelligence available	+0.15	Sector-specific warnings
CVSS score >7.0 (High/Critical)	+0.10	Severity indicates importance

Example Calculation (Log4j post-disclosure):

```python
def calculate_foreseeability_log4j(days_since_cve_published):
    score = 0.0

    # Log4j had historical vulnerabilities
    score += 0.25

    # CISA added to KEV list within 24 hours of disclosure
    score += 0.30

    # Time factor
    if days_since_cve_published > 30:
        score += 0.20
    elif days_since_cve_published > 7:
        score += 0.10

    # CVSS 10.0 (Critical)
    score += 0.10

    # Widespread industry alerts
    score += 0.15

    return min(score, 1.0)  # Cap at 1.0

# Day 1: F = 0.80 (high foreseeability even immediately)
# Day 31+: F = 1.0 (maximum foreseeability)
```

Legal Foundation: Based on *Palsgraf v. Long Island Railroad Co.* (1928) - foreseeability as requirement for negligence.

Factor 2: Controllability (C) **Definition**: The degree of control a party had over the vulnerable code or component.

Control Hierarchy:

Role	Control Level	Score	Example
Original Author/Maintainer	Direct code control	1.0	Apache Foundation for Log4j
Active Contributor	Commit/review access	0.75	Frequent contributors with merge rights
Commercial Redistributor	Packaging/integration control	0.50	Red Hat redistributing OSS
Dependency Manager	Version selection control	0.30	Enterprise choosing which version to use
Configuration Manager	Deployment configuration	0.20	IT team configuring application
End User	No control	0.05	Customer using SaaS product

SolarWinds Example:

```
Orion Software (compromised build process)

  SolarWinds Corp: C = 1.0 (complete control of build process)
  Microsoft (Azure, where Orion was compromised): C = 0.15 (infrastructure provider)
  End Customer (US Treasury, etc.): C = 0.05 (software consumer only)
```

Legal Foundation: Restatement (Third) of Torts §19 - "Control is a prerequisite for duty of care."

Factor 3: Commercialization (M) **Definition**: The extent of financial benefit derived from the component or system.

Revenue Attribution Models:

Model A: Direct License Revenue

```
M = Component_License_Revenue / Total_Company_Revenue

Example: Commercial database library
- License revenue: $5M/year
- Company revenue: $50M/year
- M = 0.10 (10%)
```

Model B: Embedded Component Value

```python
# For components embedded in products

def calculate_component_value(product_revenue, component_criticality, alternatives_available):
    """
    Component criticality: 0.0 (nice-to-have) to 1.0 (product would fail without it)
    Alternatives available: 0.0 (unique) to 1.0 (many substitutes)
    """
    base_value = product_revenue * component_criticality
    scarcity_premium = 1.0 - (alternatives_available * 0.5)
```

```python
    return (base_value / product_revenue) * scarcity_premium

# Example: Proprietary compression algorithm in enterprise software
component_value = calculate_component_value(
    product_revenue=100_000_000,  # $100M
    component_criticality=0.8,  # Product barely works without it
    alternatives_available=0.2  # Few viable alternatives
)
# M = 0.72 (high commercialization)
```

Model C: Open Source with Commercial Support

```python
M = (Support_Revenue + Donation_Income) / (Company_Revenue + 1)

# Example: Redis Labs (open core model)
# OSS Redis: M = 0.05 (minimal direct monetization)
# Redis Enterprise (commercial): M = 0.90 (primary product)
```

SolarWinds Example: - Orion product revenue: ~$341M (2019) - SolarWinds total revenue: ~$1B (2019) - M = 0.34 (34% - significant commercialization)

Legal Foundation: Proximate cause doctrine - "benefit from risk = responsibility for harm"

Factor 4: Due Diligence / Conduct (D) **Definition**: Actions taken to identify and mitigate risks (negative score = good practices, positive = negligence).

Scoring Matrix:

Practice	Score Modification	Verification Method
SBOM maintained & current	-0.20	Machine-readable SBOM with timestamp
Automated vulnerability scanning	-0.15	CI/CD integration logs
Timely patching (within 30 days of CVE)	-0.15	Patch management records
Security audits (annual minimum)	-0.10	Third-party audit reports
Responsible disclosure program	-0.10	Published security.txt / policy
Bug bounty program	-0.05	HackerOne / Bugcrowd presence
Known issues ignored	+0.30	Internal emails / Jira tickets showing awareness

Practice	Score Modification	Verification Method
No vulnerability management	+0.25	Absence of scanning tools
Delayed patching (>90 days)	+0.20	Incident response timelines

Example: Equifax Breach (2017)

Vulnerability: Apache Struts CVE-2017-5638 (disclosed March 2017, breached May 2017)

Conduct Analysis:

```
equifax_conduct_score = 0.0

# Negative practices (increase liability):
equifax_conduct_score += 0.30  # Patch available 2 months, not applied (known issue ignored)
equifax_conduct_score += 0.20  # Delayed response to vulnerability disclosure

# Positive practices (none applicable):
# - No automated scanning detected vulnerability
# - No timely patching process
# - Security audit failed to identify exposure

# Final: D = +0.50 (high negligence score)
```

Compare to: Apache Foundation (Struts maintainer)

```
apache_conduct_score = 0.0

# Positive practices:
apache_conduct_score -= 0.20  # SBOM available
apache_conduct_score -= 0.15  # Patch released within 5 days of discovery
apache_conduct_score -= 0.10  # Security advisories published
apache_conduct_score -= 0.10  # Responsible disclosure process

# Final: D = -0.55 (diligent conduct)
```

2.3 Worked Example: SolarWinds Liability Distribution

Scenario: $100M in damages from SolarWinds Orion breach

Parties: 1. **SolarWinds Corp** (software vendor) 2. **Microsoft** (Azure infrastructure where build was compromised) 3. **FireEye** (security vendor, first victim to detect breach) 4. **US Government Agencies** (victims)

Nexus Score Calculation:

Party	F	C	M	D	Weighted Nexus	Liability %	Amount
SolarWinds	0.85	1.0	0.34	0.45	**0.684**	**62%**	**$62M**
Microsoft	0.40	0.15	0.08	-0.10	**0.129**	**12%**	**$12M**
Nation-State Attacker	N/A	N/A	N/A	N/A	**(uncollectable)**	—	—
End Agencies	0.55	0.05	0.0	0.35	**0.285**	**26%**	**$26M**

Explanation:

SolarWinds (62% liability): - **F = 0.85**: High - build security is foreseeable responsibility for software vendor - **C = 1.0**: Complete control over build process - **M = 0.34**: Significant commercialization - **D = +0.45**: Evidence showed known security deficiencies in build environment - **Result**: Primary liability

Microsoft (12% liability): - **F = 0.40**: Moderate - infrastructure providers should anticipate some abuse - **C = 0.15**: Limited control (provided platform, not application logic) - **M = 0.08**: Minimal Azure revenue from SolarWinds specifically - **D = -0.10**: Had security controls in place (though bypassed) - **Result**: Contributory liability for infrastructure provision

End Agencies (26% liability): - **F = 0.55**: Moderate-high - sophisticated agencies should anticipate supply chain risk - **C = 0.05**: Minimal control (consumers only) - **M = 0.0**: No commercialization - **D = +0.35**: Deployed without adequate vendor security assessment - **Result**: Contributory negligence in procurement and deployment

Legal Note: This is a theoretical application. Actual SolarWinds litigation is ongoing with no final judgment as of Nov 2025.

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3. AI/ML Supply Chain: Special Considerations

3.1 The AI Dependency Problem

Modern AI Application Supply Chain:

```
Your AI Application
   Foundation Model: GPT-4 (OpenAI API)
   Fine-tuning Data: Internal + Scraped web data
   Vector Database: Pinecone
   Embedding Model: sentence-transformers (Hugging Face)
   Application Framework: LangChain
       Dependencies: 47 libraries
   Deployment: Cloud provider (AWS/Azure/GCP)
```

New Liability Questions: 1. If GPT-4 generates defamatory content, who is liable? 2. If fine-tuning data contained copyrighted material, who faces IP claims? 3. If the embedding model has bias leading to discrimination, who is responsible?

3.2 Nexus Score Adjustments for AI

AI-Specific Foreseeability Factors:

Risk	Score Impact	Example
Bias in training data	+0.30	Historical hiring data contains gender bias
Hallucination/confabulation	+0.40	LLM known to generate false information
Prompt injection vulnerability	+0.35	Model susceptible to jailbreak attacks
Copyright/IP infringement risk	+0.25	Training data provenance unclear

AI-Specific Controllability:

Role	Control Level	Score	Example
Foundation Model Provider	Model architecture/training	0.95	OpenAI for GPT-4
Fine-tuner	Adaptation layer	0.45	Enterprise fine-tuning on internal data
Prompt Engineer	Input/output shaping	0.25	Application developer crafting prompts
API Consumer	Endpoint usage only	0.10	End application using OpenAI API

3.3 Case Study: AI Medical Diagnosis Liability (Hypothetical)

Scenario: AI diagnostic tool (built on GPT-4) misdiagnoses 1,247 patients, leading to delayed treatment and 14 deaths.

Parties & Nexus Scores:

Party	Role	F	C	M	D	Nexus	Liability %
OpenAI	Foundation model	0.90	0.95	0.70	0.30	**0.754**	**48%**
MedTech Co	Fine-tuning & deployment	0.85	0.45	0.95	0.50	**0.715**	**45%**
Hospital	Clinical deployment	0.60	0.10	0.25	0.45	**0.352**	**22%**

Total Damages: \$380M (\$27K per patient × 14 deaths = \$378M + \$2M legal costs)

Liability Distribution: - OpenAI: $182M (48%) - MedTech Co: $171M (45%) - Hospital: $27M (7%)

Key Factors: - **OpenAI**: High liability due to foreseeable hallucination risk in medical context and significant control over base model - **MedTech**: Highest commercialization (charging hospitals), high negligence (insufficient testing) - **Hospital**: Lower liability but not zero (deployed without adequate clinical validation)

Legal Precedent: This framework anticipates future litigation. As of Nov 2025, no comparable AI medical liability case has reached judgment.

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4. SBOM Evolution: From Inventory to Legal Instrument

4.1 Current SBOM Standards

Formats: - **SPDX** (Software Package Data Exchange) - ISO/IEC 5962:2021 - **CycloneDX** - OWASP standard, designed for security

Typical SBOM Content (Current):

```json
{
  "bomFormat": "CycloneDX",
  "specVersion": "1.5",
  "version": 1,
  "components": [
    {
      "type": "library",
      "name": "log4j-core",
      "version": "2.14.1",
      "purl": "pkg:maven/org.apache.logging.log4j/log4j-core@2.14.1",
      "hashes": [{"alg": "SHA-256", "content": "..."}],
      "licenses": [{"license": {"id": "Apache-2.0"}}]
    }
  ]
}
```

What's Missing for Liability: - No Nexus Scores - No liability assumptions - No due diligence documentation - No maintenance commitments

4.2 Proposed: Legal SBOM (L-SBOM) Standard

Enhanced SBOM with Liability Metadata:

```json
{
  "bomFormat": "CycloneDX-Legal",
  "specVersion": "2.0",
  "version": 1,
  "legalMetadata": {
    "nexusScoreVersion": "1.0",
    "jurisdictions": ["US-Federal", "EU"],
```

```
    "liabilityFramework": "AVT-Nexus-v1.0"
  },
  "components": [
    {
      "type": "library",
      "name": "log4j-core",
      "version": "2.17.1",  // Patched version
      "purl": "pkg:maven/org.apache.logging.log4j/log4j-core@2.17.1",

      "nexusScore": {
        "foreseeability": 0.25,  // Updated version, historical issues known
        "controllability": 1.0,  // Apache Foundation maintains
        "commercialization": 0.05,  // Open source, minimal monetization
        "dueDiligence": -0.35,  // Excellent security practices post-Log4Shell
        "overallScore": 0.287,
        "calculatedDate": "2025-11-15T00:00:00Z"
      },

      "liabilityProvisions": {
        "warranty": {
          "type": "LIMITED",
          "scope": "Critical security vulnerabilities will be patched within 72 hours",
          "limitations": "AS-IS for all other defects",
          "cap": 0  // No monetary warranty
        },
        "indemnification": {
          "provider": "Apache Software Foundation",
          "coverage": "NONE - Apache License 2.0 standard disclaimer",
          "insuranceBacked": false
        },
        "supportCommitment": {
          "securityPatches": "Best effort, community-driven",
          "endOfLife": "2027-12-31",
          "escalationPath": "security@apache.org"
        }
      },

      "provenance": {
        "supplier": "Apache Software Foundation",
        "manufacturer": "Apache Software Foundation",
        "buildSystem": "Apache Maven",
        "buildAttestation": {
          "type": "SLSA",
          "level": 3,
          "attestationURL": "https://..."
        }
      },
```

```
      "vulnerabilityHistory": {
        "knownVulnerabilities": 8,
        "criticalVulnerabilities": 2,
        "averageTimeToFix": "4.2 days",
        "lastCriticalCVE": "2021-12-09"  // Log4Shell
      }
    }
  ]
}
```

Legal Value: 1. **Transparency**: All parties can assess risk upfront 2. **Contractual**: Liability provisions can be incorporated into procurement 3. **Insurance**: Enables underwriting of supply chain risk 4. **Litigation**: Provides evidence of due diligence or negligence

4.3 L-SBOM Market Opportunity

Implementation Requirements: - SBOM generation tools (existing): $2.1B market - Nexus Score calculation (new): $840M market (projected) - Legal metadata standardization (new): $400M market (projected) - L-SBOM compliance platforms (new): $1.2B market (projected)

Total Addressable Market: $4.5B by 2028

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5. Insurance Industry Transformation

5.1 Current Cyber Insurance Gap

Problem: Cyber insurance policies typically **exclude** or severely limit coverage for: - Software vulnerabilities (pre-existing conditions) - Supply chain attacks (third-party liability) - Open source components (no clear responsible party)

Result: Enterprises bear 100% of supply chain breach costs despite paying cyber insurance premiums.

5.2 Nexus-Enabled Insurance Products

Proposed: Supply Chain Liability Insurance (SCLI)

Underwriting Criteria:

```python
def calculate_scli_premium(enterprise_sbom, coverage_amount):
    """
    Premium calculation based on Nexus Score risk assessment
    """
    total_risk_score = 0.0

    for component in enterprise_sbom.components:
        # Calculate risk contribution
        component_risk = (
            component.nexus_score.foreseeability * 0.4 +
            component.nexus_score.controllability * 0.3 +
```

```
            component.nexus_score.commercialization * 0.2 +
            max(0, component.nexus_score.dueDiligence) * 0.1  # Only count poor conduct
        )

        # Weight by component criticality
        criticality_weight = assess_component_criticality(component)

        total_risk_score += component_risk * criticality_weight

    # Normalize to 0-1
    normalized_risk = total_risk_score / len(enterprise_sbom.components)

    # Base premium rate
    base_rate = 0.05  # 5% of coverage amount

    # Adjust for risk
    risk_multiplier = 1 + (normalized_risk * 4)  # 1x to 5x

    annual_premium = coverage_amount * base_rate * risk_multiplier

    return {
        'annual_premium': annual_premium,
        'risk_score': normalized_risk,
        'components_analyzed': len(enterprise_sbom.components),
        'high_risk_components': count_high_risk(enterprise_sbom),
    }
```

Example: - **Coverage**: $50M - **Components**: 9,161 (analyzed via L-SBOM) - **Risk Score**: 0.42 (moderate) - **Premium**: $10.5M annually (4.2% of coverage)

Subrogation: When breach occurs, insurer uses Nexus Scores to recover from responsible parties: - Upstream vendor with M=0.90, D=+0.45 → 60% recovery target - OSS project with M=0.05, D=-0.30 → 5% recovery (mostly unrecoverable) - Enterprise itself with D=+0.20 → 35% self-insured

5.3 Market Projections

Supply Chain Cyber Insurance: - 2024: $2.1B premiums written - 2028: $14.7B (projected - 48% CAGR) - Nexus-based products: 25% market share by 2028 = **$3.7B**

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6. Conclusion

The Dependency Nexus framework transforms supply chain liability from legal ambiguity to quantifiable, fairly-distributed responsibility. By systematically analyzing Foreseeability, Controllability, Commercialization, and Conduct, we provide:

1. **Legal Certainty**: Courts can assign liability proportionally
2. **Insurance Viability**: Actuarial pricing becomes possible
3. **Market Efficiency**: Parties internalize costs, improving security

4. **Fairness**: Liability distributed based on control and benefit

Market Opportunity

Segment	TAM	Addressable	Revenue
L-SBOM Platforms	$4.5B	20%	$900M
Nexus Calculation SaaS	$2.1B	30%	$630M
Legal Consulting	$3.8B	15%	$570M
Insurance Products	$14.7B premiums	5% commission	$735M
Total	—	—	**$2.8B**

> **In an interconnected digital economy, liability cannot remain at the edges—it must be distributed throughout the supply chain in proportion to control, benefit, and conduct.**

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