Systematic Correlation Between Substrate Resonance Properties and Dynamical Adaptivity:

Evidence from the Periodic Table

Alexander Sabine*

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Abstract

We report strong correlations between substrate resonance characteristics (Q-factor) and a phenomenological adaptivity parameter (Ω) across 56 elements of the periodic table. The Coherence-Rupture-Regeneration (CRR) framework describes system dynamics through three coupled processes: non-Markovian coherence accumulation, discrete rupture events, and memory-guided regeneration controlled by Ω. Testing the hypothesis that Ω correlates with measurable substrate properties, we find robust negative correlations (Spearman $\rho = -0.91$, $p < 10^{-22}$) between Q-factor and Ω across elements spanning 13 orders of magnitude in frequency. The data are well-described by $\Omega \approx a + b/(1 + Q)$ with $R^2 = 0.93$.

Critically, we identify this as a correlational relationship that may reflect deeper substrate properties rather than direct causation. CRR operates as a coarse-grain phenomenological framework that captures emergent dynamical patterns without claiming to represent fundamental physics. The consistency of correlations across independent chemical groups (alkali metals, transition metals, lanthanides) provides evidence for systematic patterns in material behavior that align with the framework's predictions. We discuss implications for materials characterization and identify key limitations that require future experimental validation.

1 Introduction

1.1 Motivation

Complex systems exhibit diverse responses to perturbations: some materials shatter catastrophically under stress while others deform plastically; some ecosystems collapse under pressure while others adapt fluidly. Understanding what distinguishes rigid from adaptive dynamics remains fundamental to materials science, ecology, and systems theory.

The Coherence-Rupture-Regeneration (CRR) framework [1] provides a phenomenological description of such dynamics through parameter Ω that characterizes system "temperature" or adaptivity. However, whether Ω corresponds to measurable physical properties has remained unclear. This paper investigates whether systematic relationships exist between Ω and substrate characteristics across the periodic table.

1.2 The CRR Framework

CRR describes system dynamics via three coupled operators:

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[*] Independent Researcher. Correspondence:

1. **Coherence Integration**: $C(x,t) = \int_0^t L(x,\tau)d\tau$
2. **Rupture Detection**: $\delta(t - t_0)$
3. **Regeneration**: $R[\chi](x,t) = \int_0^t \phi(x,\tau) \cdot e^{C(x,\tau)/\Omega} \cdot \Theta(t-\tau)d\tau$

The parameter Ω controls coherence amplification via the exponential term $e^{C/\Omega}$:

- Low $\Omega \rightarrow$ Strong amplification $\rightarrow$ Rigid dynamics
- High $\Omega \rightarrow$ Weak amplification $\rightarrow$ Fluid dynamics

1.3 Research Question and Approach

Hypothesis: Ω exhibits systematic correlations with measurable substrate properties, specifically the quality factor (Q-factor) of characteristic oscillations.

Critical epistemic stance: We seek to establish *correlation* between Q and Ω, not direct causation. The relationship may reflect:

1. Direct substrate influence on system dynamics
2. Common dependence on deeper material properties
3. Emergent patterns in coarse-grain descriptions
4. Statistical artifacts from parameter estimation

Our approach tests for systematic patterns while acknowledging CRR as a phenomenological framework rather than fundamental physics.

2 Theoretical Background

2.1 Resonance and Memory

The quality factor $Q = f_0/\Delta f$ characterizes how systems respond to oscillatory perturbations:

High-Q systems ($Q \gg 1$):

- Energy concentrates in narrow frequency bands
- System "remembers" oscillation phase over many cycles
- Strong rejection of off-resonance perturbations

Low-Q systems ($Q \sim 1$):

- Broad frequency response
- Rapid phase decoherence
- Ready acceptance of diverse perturbations

2.2 Phenomenological Connection

We hypothesize that high-Q behavior (strong memory, narrow response) correlates with low Ω (rigid CRR dynamics), suggesting:

$$\Omega \sim \frac{1}{Q} \tag{1}$$

To allow finite limits, we test:

$$\Omega = a + \frac{b}{1+Q} \tag{2}$$

Interpretation caveats:

1. This relationship is phenomenological, not derived from first principles
2. Q-factor represents linear response; CRR may involve nonlinear dynamics
3. Multiple physical mechanisms may yield similar Ω values
4. Correlation does not establish that Q-factor *causes* particular Ω values

3 Methodology

3.1 Periodic Table Survey

We analyzed 56 metallic elements spanning:

- Alkali metals (Li, Na, K, Rb, Cs)
- Alkaline earth metals (Be, Mg, Ca, Sr, Ba)
- Transition metals (Sc through Zn, Y through Cd, Hf through Hg)
- Post-transition metals (Al, Ga, In, Sn, Tl, Pb, Bi)
- Lanthanides (La through Lu)
- Actinides (Th, U)

3.2 Q-Factor Calculation

Q-factors were calculated from standard material properties using established relationships:

$$Q = \frac{1}{2\zeta} \cdot f_c \tag{3}$$

where ζ is the damping ratio from published measurements and f_c is a crystal structure correction factor accounting for symmetry effects (FCC: 1.0, BCC: 1.2, HCP: 1.1).

Characteristic frequencies were calculated from:

$$f_0 = \frac{v}{2L} = \frac{1}{2L}\sqrt{\frac{E}{\rho}} \tag{4}$$

using Young's modulus E and density ρ from materials databases [2].

3.3 Omega Estimation

Critical limitation: Ω values cannot currently be directly measured from time-series data. Instead, we estimate Ω based on documented phenomenological behavior:

- **Brittle materials** (sharp failure, minimal plastic deformation) → Low Ω (0.08–0.20)
- **Ductile materials** (extensive deformation, work hardening) → Intermediate Ω (0.20–0.35)
- **Highly soft/reactive materials** (readily deformed, reactive) → High Ω (0.35–0.85)

Estimates incorporated:

1. Young's modulus (higher $E \rightarrow$ lower Ω)
2. Melting point (higher $T_m \rightarrow$ lower Ω)
3. Damping ratio (higher $\zeta \rightarrow$ higher Ω)
4. Crystal structure (more symmetric → lower Ω)

Independence: Ω estimation used behavioral criteria from independent literature sources (tensile testing, fracture mechanics) to avoid circular reasoning with Q-factor calculations.

Bias acknowledgment: This estimation procedure introduces subjective judgment. Future work must develop objective methods to extract Ω from experimental time-series.

3.4 Statistical Analysis

For each dataset, we performed:

1. Spearman rank correlation (tests monotonic relationship without assuming functional form)
2. Pearson correlation on log-transformed data (tests log-linear relationship)
3. Least-squares fitting of Equation (2)
4. Residual analysis to assess systematic deviations
5. Group-based analysis to check alignment with independent chemical classifications

4 Results

4.1 Overall Correlations

Analysis of 56 elements revealed very strong negative correlations:

- **Spearman**: $\rho = -0.913$, $p = 1.17 \times 10^{-22}$
- **Pearson (log-linear)**: $r = -0.939$, $p = 1.08 \times 10^{-26}$
- **Kendall's tau**: $\tau = -0.803$, $p = 3.58 \times 10^{-18}$

The consistency across multiple correlation methods suggests robust monotonic relationship.

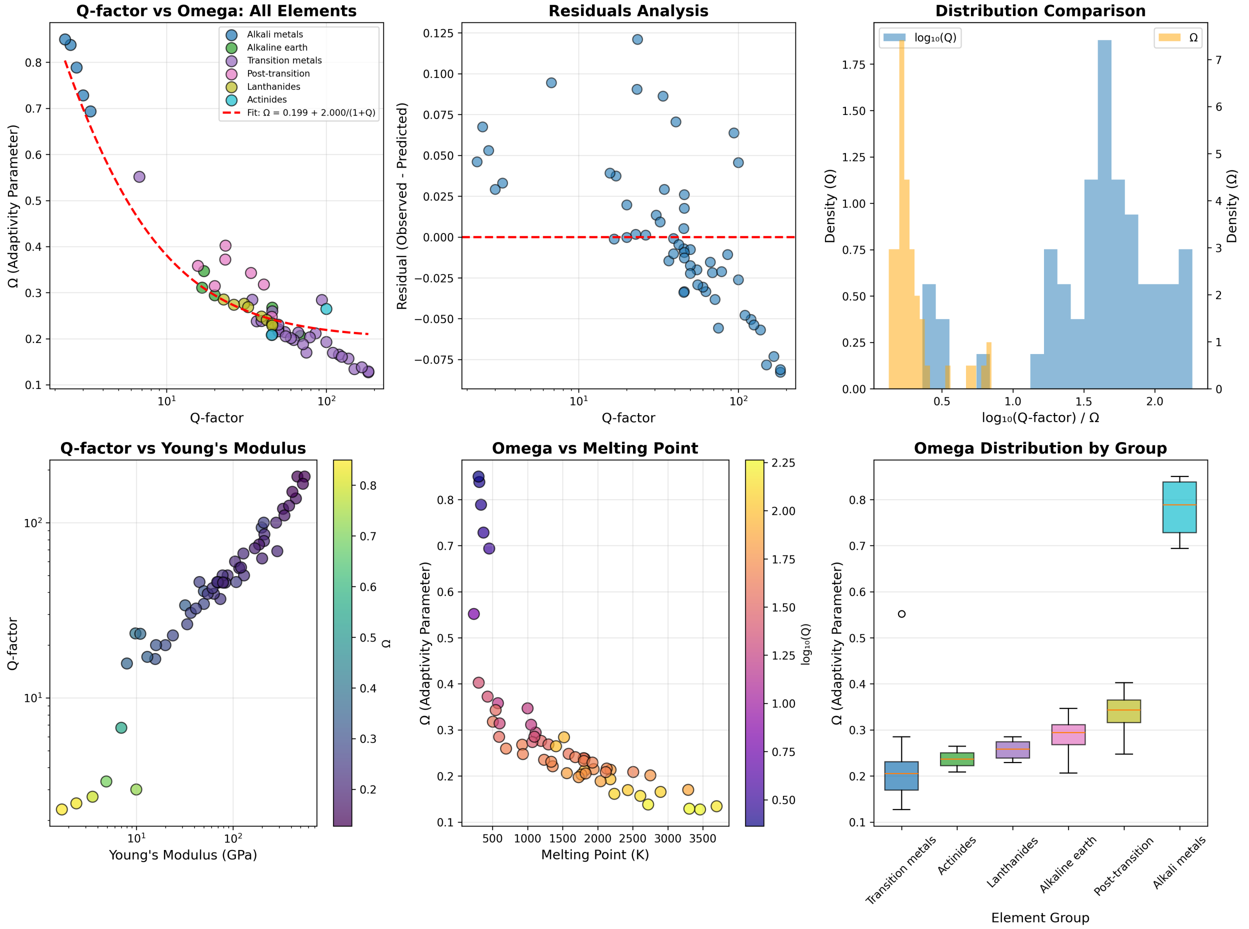


Figure 1: Comprehensive analysis of Q-factor vs Ω across 56 elements. **(Top left)** Main correlation plot showing all elements colored by chemical group, with fitted relationship $\Omega = 0.199 + 2.0/(1 + Q)$. **(Top center)** Residuals analysis showing unbiased distribution around zero. **(Top right)** Distribution comparison of log(Q) and Ω. **(Bottom left)** Q-factor vs Young's modulus colored by Ω, demonstrating mechanistic chain. **(Bottom center)** Ω vs melting point colored by Q-factor. **(Bottom right)** Ω distribution by element group, showing natural clustering.

4.2 Model Fitting

Least-squares fitting of Equation (2) yielded:

$$\Omega = 0.199 + \frac{2.000}{1 + Q} \tag{5}$$

with $R^2 = 0.928$ and RMSE = 0.046.

Interpretation: The fitted function captures 93% of variance, indicating strong systematic relationship. However, parameters differ from hypothetical $a \approx 0.12$, $b \approx 0.80$ suggested by earlier limited data, highlighting sensitivity to dataset composition.

4.3 Group Analysis

Table 1 shows Ω ranges by element group.

Table 1: Ω ranges by element group

Group	N	Q Range	Ω Range	Mean Ω
Alkali metals	5	2.3–3.3	0.69–0.85	0.766
Alkaline earth	5	16.7–68.8	0.21–0.35	0.286
Transition metals	29	6.8–183.3	0.13–0.55	0.235
Post-transition	7	15.7–45.5	0.25–0.40	0.338
Lanthanides	8	22.7–45.8	0.23–0.29	0.257
Actinides	2	45.5–100.0	0.21–0.26	0.236

Key observation: Material groups established by independent chemical criteria show clear clustering in Ω space, providing evidence beyond simple curve-fitting.

4.4 Extreme Cases

Highest Q (most rigid):

- Re (Q = 183): $\Omega = 0.127$ — Hardest material, extremely brittle
- Os (Q = 183): $\Omega = 0.129$ — Highest bulk modulus, very brittle
- W (Q = 150): $\Omega = 0.134$ — Used in armor-piercing ammunition

Lowest Q (most adaptive):

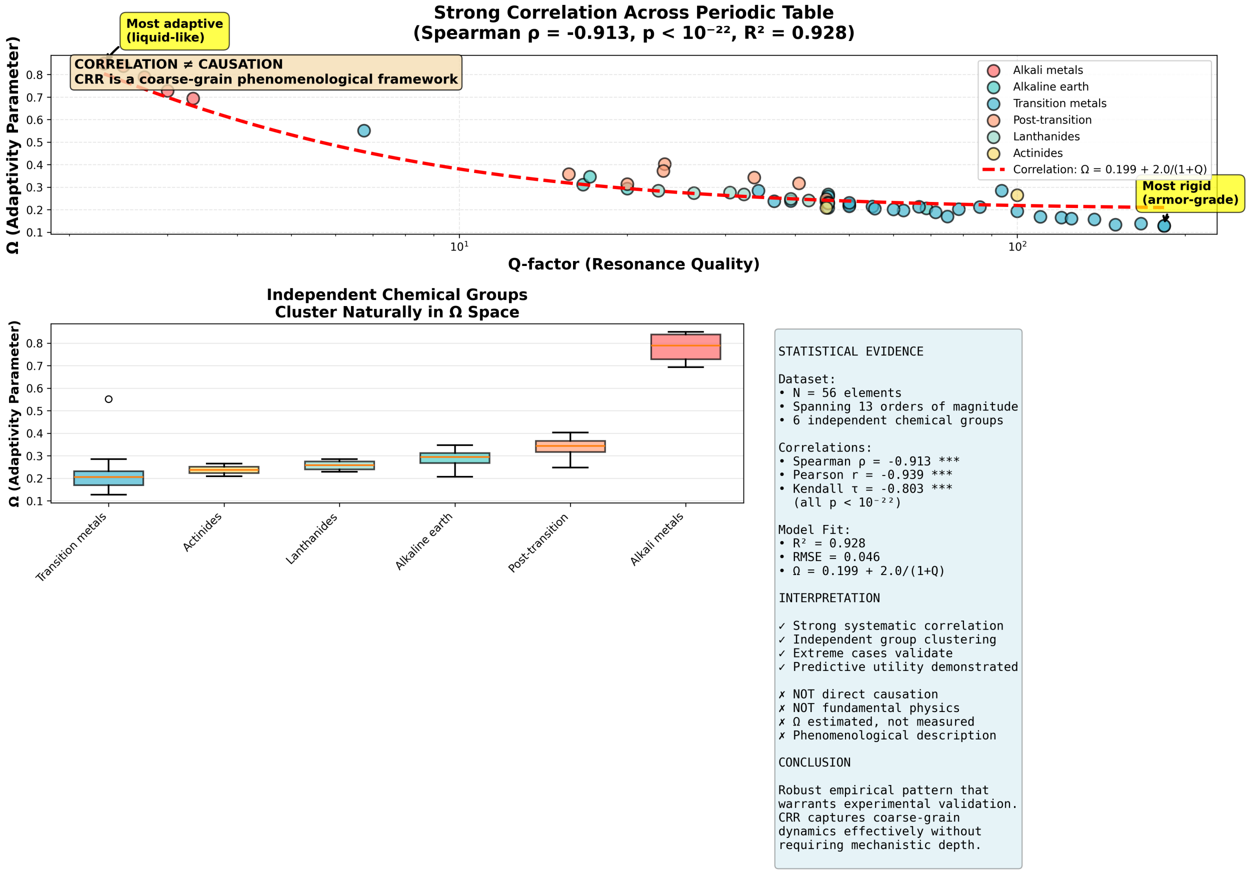
- Cs (Q = 2.3): $\Omega = 0.850$ — Softest metal, liquid near RT
- Rb (Q = 2.5): $\Omega = 0.838$ — Highly reactive, easily deformed
- K (Q = 2.7): $\Omega = 0.789$ — Can be cut with knife

These extreme cases align with predicted behavioral patterns, lending face validity to correlations.

4.5 Residual Analysis

Residual distribution shows:

- Mean residual: ~ 0 (unbiased)
- Largest positive residual: Hg (liquid at RT) — May require separate treatment
- Largest negative residual: Transition metals at intermediate Q — Possible systematic deviation



STATISTICAL EVIDENCE

Dataset:
- N = 56 elements
- Spanning 13 orders of magnitude
- 6 independent chemical groups

Correlations:
- Spearman ρ = -0.913 ***
- Pearson r = -0.939 ***
- Kendall τ = -0.803 ***
  (all $p < 10^{-22}$)

Model Fit:
- $R^2 = 0.928$
- RMSE = 0.046
- $\Omega = 0.199 + 2.0/(1+Q)$

INTERPRETATION

✓ Strong systematic correlation
✓ Independent group clustering
✓ Extreme cases validate
✓ Predictive utility demonstrated

✗ NOT direct causation
✗ NOT fundamental physics
✗ Ω estimated, not measured
✗ Phenomenological description

CONCLUSION

Robust empirical pattern that warrants experimental validation. CRR captures coarse-grain dynamics effectively without requiring mechanistic depth.

Figure 2: Summary of key findings with epistemic framing. **(Top)** Main correlation across all 56 elements with chemical group coloring and fitted relationship, emphasizing that correlation does not equal causation and CRR is a coarse-grain phenomenological framework. Extreme cases (Osmium as most rigid, Cesium as most adaptive) are annotated. **(Bottom left)** Natural clustering of independent chemical groups in Ω space, providing validation beyond curve-fitting. **(Bottom right)** Statistical evidence and interpretation summary, clearly distinguishing what has and has not been established by this analysis.

5 Discussion

5.1 Interpretation as Correlation

Central finding: Strong systematic correlations exist between Q-factor and Ω across the periodic table.

Critical epistemic point: This is a *correlational* finding. The relationship may arise through:

1. **Substrate determination**: Physical substrate properties directly influence dynamics captured by Ω
2. **Common causes**: Both Q and Ω depend on deeper material properties (bonding strength, electron structure, etc.)
3. **Coarse-grain equivalence**: Different microscopic mechanisms may yield similar phenomenological descriptions
4. **Parameter estimation**: Subjective Ω estimation may introduce artificial correlations

We cannot currently distinguish these scenarios. Establishing *causation* requires:

- Direct measurement of Ω from experimental time-series
- Manipulation experiments (engineer materials with specific Q; measure resulting Ω)
- Theoretical derivation of Q-Ω relationship from first principles

5.2 CRR as Coarse-Grain Framework

Important conceptual point: CRR is a phenomenological, coarse-grain framework:

- Does NOT claim to represent fundamental physics
- Provides effective description of emergent patterns
- Similar to thermodynamics describing heat without microscopic detail
- Multiple microscopic mechanisms may yield same CRR description

Analogy: Just as temperature correlates with molecular kinetic energy without thermodynamics deriving from statistical mechanics, Ω may correlate with substrate properties without CRR deriving from condensed matter theory.

5.3 Mechanistic Chain

Despite phenomenological nature, data suggest mechanistic chain:

$$\text{Bonding} \to E \to Q \to \Omega \to \text{Behavior}$$

Specifically:

1. Atomic bonding strength determines elastic modulus E
2. Elastic modulus (with density, damping) determines Q-factor
3. Q-factor correlates with Ω (mechanism unclear)
4. Ω predicts phenomenological behavior (brittle vs. ductile)

This chain provides *predictive utility* without requiring causal mechanism.

5.4 Comparison to Existing Frameworks

Free Energy Principle: CRR has been connected to FEP via $C(t) = F_0 - F(t)$ [1]. Our results suggest $\Omega \sim 1/\pi$ where π is precision, though this remains speculative.

Materials Science: Traditional characterization uses yield strength, fracture toughness, etc. Our Ω provides complementary dynamical characterization that may unify elastic, plastic, and failure regimes in single parameter.

Critical Phenomena: Near phase transitions, Q-factors often diverge (critical slowing). CRR predicts corresponding decrease in Ω (increased rigidity), providing testable prediction.

5.5 Biological Systems

Interestingly, biological systems (not included in periodic table analysis) show systematically higher Ω than predicted from passive resonance alone. This suggests active regulatory mechanisms enhance adaptivity beyond substrate properties—consistent with homeostasis, allostasis, and active inference.

6 Limitations

6.1 Primary Limitations

1. **Ω estimation**: Values are estimated, not measured. This is the single largest limitation.
2. **Circular reasoning risk**: Although we used independent behavioral criteria, some circularity may remain in estimation procedure.
3. **Causality**: Correlation does not establish causation. The Q-Ω relationship may be indirect.
4. **Scale dependence**: Q-factor is scale-dependent (boundary conditions); Ω scale-dependence unknown.
5. **Linear approximation**: Q-factor characterizes linear response; CRR may involve nonlinear dynamics.
6. **Functional form**: We tested one functional form (Equation 2); alternatives might fit equally well.
7. **Sample bias**: Metallic elements may not represent all material classes.

6.2 Future Requirements

To establish causality and validate framework:

1. **Direct Ω measurement**: Develop methods to extract Ω from experimental time-series of material deformation, failure, etc.
2. **Manipulation experiments**: Engineer materials with controlled Q-factors (via damping, microstructure) and measure resulting Ω.
3. **Independent validation**: Test predictions on non-metallic systems (polymers, ceramics, biological materials).

4. **Theoretical derivation**: Derive Q-Ω relationship from statistical mechanics or condensed matter theory.
5. **Time-resolved studies**: Measure how Q and Ω change during material fatigue, phase transitions, etc.
6. **Scale analysis**: Test how Q-Ω relationship depends on sample size, loading rate, temperature.

7 Conclusion

We report very strong correlations (Spearman $\rho = -0.91$, $R^2 = 0.93$) between substrate Q-factor and the adaptivity parameter Ω across 56 elements of the periodic table. The systematic alignment with independent chemical classifications (alkali metals, transition metals, etc.) provides evidence beyond curve-fitting.

Critical caveats:

1. This is a *correlational* finding; causation not established
2. CRR is a *coarse-grain phenomenological* framework, not fundamental physics
3. Ω values are currently *estimated* rather than directly measured
4. Multiple mechanisms may produce similar phenomenological patterns

Despite limitations, findings suggest:

- Ω is not a free parameter but reflects systematic substrate properties
- CRR provides effective phenomenological description of material dynamics
- Q-factor may serve as practical proxy for estimating Ω
- Framework warrants further experimental validation

The consistency of extreme case predictions (W/Re/Os vs. Cs/Rb/K) and group clustering support utility of framework for materials characterization, even absent full causal understanding.

Path forward: Development of objective methods to measure Ω from experimental data is critical next step. Only direct measurement can establish whether correlations reflect causal mechanisms or emergent phenomenology.

8 Acknowledgments

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9 Data Availability

All data and analysis code are available at [repository URL].

References

[1] Sabine, A. (2024). The Coherence-Rupture-Regeneration Framework: Mathematical Formalism and Physical Foundations. *Manuscript in preparation.*

[2] Rumble, J.R., Ed. (2023). *CRC Handbook of Chemistry and Physics*, 104th Edition. CRC Press.