レジリエンスの科学的解明に向けて

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「想定外」？

「想定外」にどう対応するか

Photo: Fukushima No.2 Plant, TEPCO

想定された津波高さ: 5.7m

3/11の津波高さ： 14m

防潮堤が14mならばよかったのか？

re･sil･i･ent

adj. 弾力性のある、回復力のある

今回のような震災に立ち向かうためには、災禍の損害から早期の機能回復が可能な技術社会システムを実現するための、レジリアンス工学とも呼ぶべき新分野を確立しなければなりません

東京大学工学系研究科 緊急工学ビジョン･ワーキンググループ 「震災後の工学は何をめざすのか」
http://www.t.u-tokyo.ac.jp/epage/topics/pdf/vision.pdf

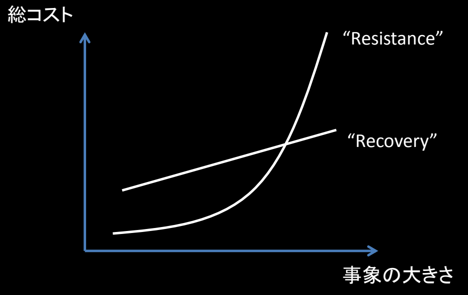
Resilience = Resistance + Recovery

Logstaff et al., “Building Resilient Communities,” Homeland Security Affairs, Vol VI, No.3, 2010

+

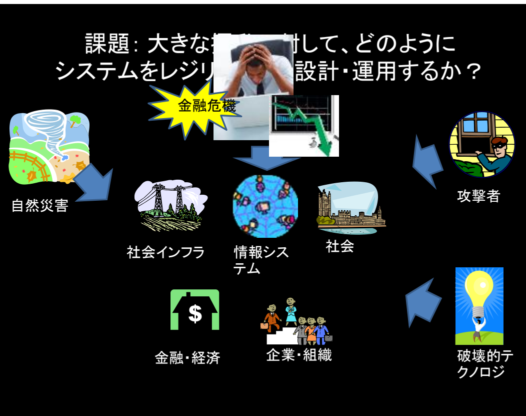
Taoi-cho, Miyagi Pref.
http://www.bousaihaku.com/cgi-bin/hp/index2.cgi?ac1=B742&ac2=&ac3=1574&Page=hpd2_view
http://fullload.jp/blog/2011/04/post-265.php

Resilience = Resistance + Recovery



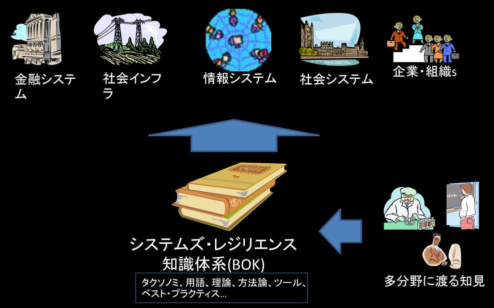
情報・システム研究機構での取り組み

情報・システム研究機構



仮説: 分野を超えた共通のレジリエンス戦略がある

目標：レジリエントなシステムを設計・運用するための知識体系



レジリエンスの共通戦略

A) 冗長性
B) 多様性
C) 適応性
D) 能動的レジリエンス

冗長性1：ワシントン湖のイトヨの場合

Threat of Trout Predation

J. Kitano, et al., "Reverse Evolution of Armor Plates in the Threespine Stickleback," *Current Biology 18*, 2008.

冗長性2：日本の電力の場合

➡ 非常に大きい冗長性!!

冗長性3: 9.11における通信の相互運用性

相互運用性は冗長性の一形態

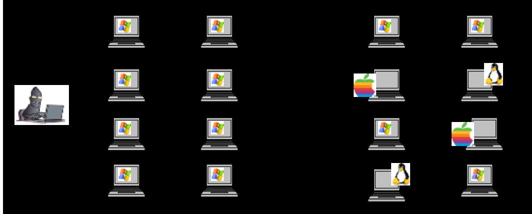
多様性1：生物はなぜ絶滅を免れてきたか

Sepp Hasslberger, "What Really Killed the Dinosaurs?
http://www.newmediaexplorer.org/sepp/2007/12/13/what_really_killed_the_dinosaurs.htm

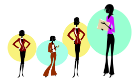
多様性2：コンピュータ・ネットワーク

"Redundancy and Diversity in Security" by Bev Littlewood and Lorenzo Strigini

一様なネットワーク(高効率)　　多様なネットワーク(resilient)



多様性をどのように測るか- 1: ばらつき



$$\sigma = \sum_{i=1}^{m} \frac{(x_i - \mu)^2}{m}$$

多様性をどのように測るか- 2: 種の多様性

p_1　p_2　p_3　…　p_N

Generalized Entropy: $G_N^{\alpha}(p_1, p_2, \ldots, p_N) = (\sum_{i=1}^{N} \frac{p_i^{\alpha}}{N})^{\frac{1}{1-\alpha}}$

Number of Types (α=0): $G_N^0(p_1, p_2, \ldots, p_N) = N$

Diversity Index (α=2): $G_N^2(p_1, p_2, \ldots, p_N) = (\sum_{i=1}^{N} \frac{p_i^2}{N})^{-1}$

準備

- Replicator Equations

$$p_i^{t+1} = p_i^t \frac{\pi_i}{\pi^t}$$

より環境に適した種の個体数が世代とともに大きくなる

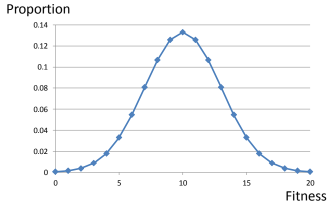
Where

p_i^t ：種*i* の時刻 *t* における個体数

π_i ：種 *i* の環境に対する適応度

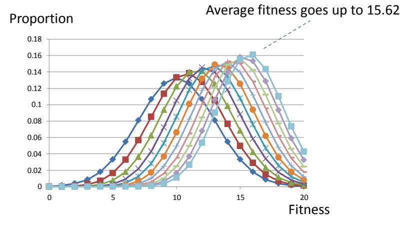
π^t ： 時刻 *t* における適応度の平均

時刻 *t=0* でのPopulation

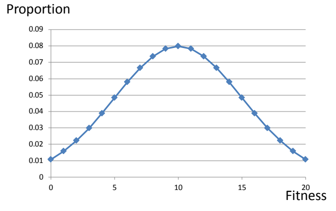


Average fitness=10, σ=3

10世代後

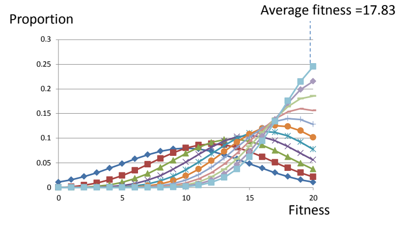


時刻 *t=0* でより大きなばらつきがあれば…



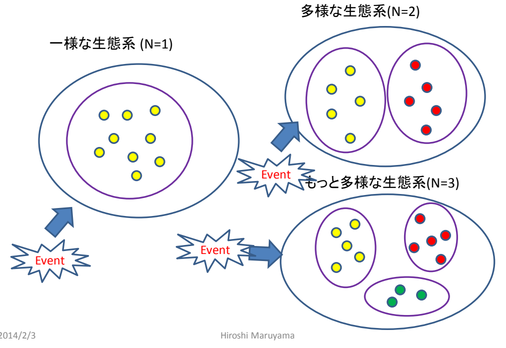
Average fitness=10, σ=5

10世代後…

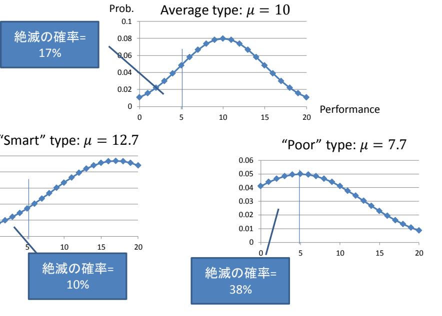


➡ *ばらつきの大きさは速い進化を可能にする*

平均化



一様な生態系の場合(N=1)



絶滅確率は、環境に適した種であってもかなり高い

中心極限定理

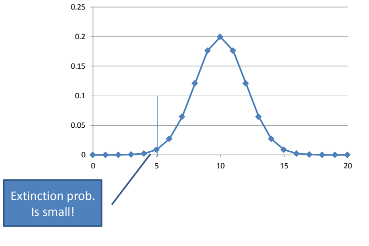
$X_1, X_2, \cdots, X_N$: 独立な確率変数、 平均値 μ 、標準偏差σ

$$\bar{X} = \sum_{i=1}^{N} \frac{X_i}{N}$$

$\bar{X}$ has mean μ and standard deviation $\frac{\sigma}{\sqrt{N}}$

大きな*N*に対して、ばらつきは小さくなる

多様な生態系においては… (N is large)



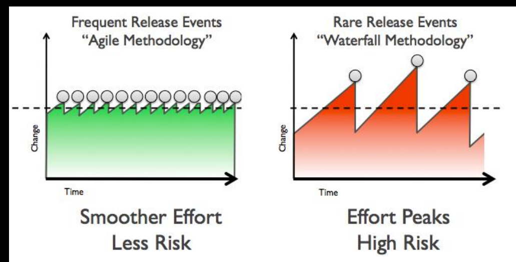
多様な生態系では、絶滅確率が小さくなる

多様性3：森林の小さな再生

“小さな擾乱を積極的に受け入れ、小さな再生やイノベーションを許すことによって、巨大な災害を軽減することができるかもしれない.”

“すべての擾乱を一律に排除するのは、おそらく最も危険な戦略”

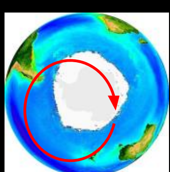
小さな擾乱を繰り返すことによるレジリエンス

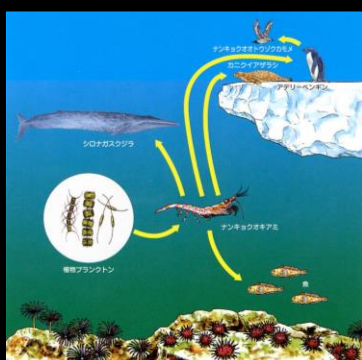


http://en.wikipedia.org/wiki/File:Agile-vs-iterative-flow.jpg

アジャイル、DevOps、GameDay/Chaos Monkey, …

多様性4：南極の生態系

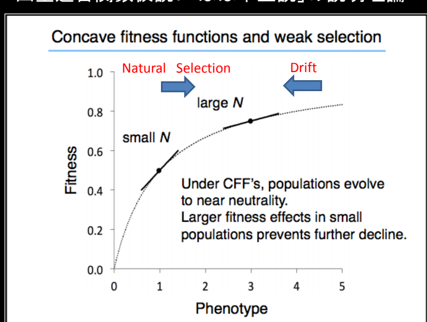




多様性をシステムに組み込むには？ — 収穫逓減の法則 (Diminishing Return)

- 夏の暑い日
  - ガリガリ君があると嬉しい
  - 2個目、たぶん嬉しい、でも1個目ほどではない
  - でも、10個目のガリガリ君の価値はほぼゼロ
- 同様の議論があちこちで見られる
  - ベルヌーイの限界効用逓減の法則
  - “Satiation” in marketing; i.e., consumers will have less utility from purchasing the same merchandise

集団遺伝学からの知見 凹型適合関数仮説：「ほぼ中立説」の説明理論



AKASHI H., OSADA N., & OHTA T., 2012 Weak selection and protein evolution. Genetics 192: 15–31

収穫低減則

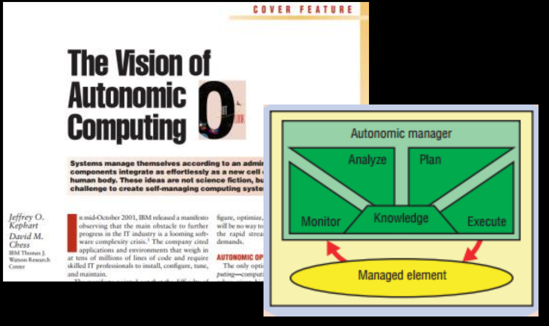
⬇

多様性

⬇

レジリエンス

適応性1：オートのミック・コンピューティング

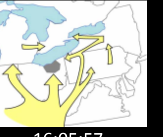


Kephart and Chess, "The Vision of Autonomic Computing," IEEE Computer, 2003.

適応性2：2003年 米国東北部大停電

- 5,500万人に影響
- オハイオの送電線の障害が、連鎖的障害を引き起こした
- 不十分な情報の共有・分析

16:05:57



16:05:57

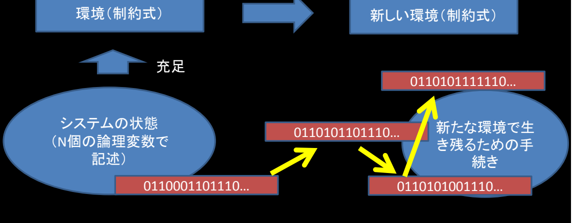
16:10:37

適応性3：ビジネスのレジリエンス

- Oct. 2002, *How Resilience Works* by Diane L. Coutu
- Sept. 2003, *The Quest for Resilience* by Gary Hamel and Liisa Välikangas
- Dec. 2012, Spotlight on *How to Manage Disruption*
  - "Surviving Disruption" by Maxwell Wessel and Clayton M. Christensen
  - "Two Routes to Resilience" by Clark Gilbert, Matthew Eyring, and Richard N. Foster
  - "Kiva the Disrupter" by Mick Mountz

レジリエンスの数理モデル

(動的)制約充足問題としてのモデル化



Example 1: Resilient Spacecraft RS-1

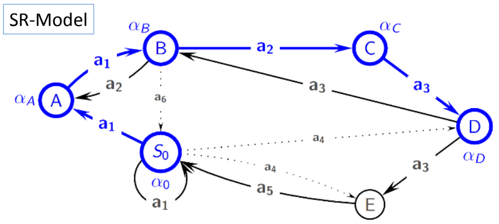
N個の部品: $X_1, X_2, \ldots, X_N$
部品の状態: {Green, Red}
Fitness: すべての部品が *Green*

外部イベントの前提:
1. 1回の事故は、高々 *k*個の部品に影響
2. 次の *k* 日間は事故は起きない

適合戦略:
- エンジニアは、1日に1つの部品を直す

⇒ RS-1 is *k*-Resilient

SR-Model：レジリエンスの計算理論的モデル



Nicolas Schwind, Tenda Okimoto, Katsumi Inoue, Hei Chan, Tony Ribeiro, Kazuhiro Minami, and Hiroshi Maruyama, "Systems Resilience: a Challenge Problem for Dynamic Constraint-Based Agent Systems," In *Proc. of the 12th International Conference on Autonomous Agents and Multiagent Systems* (AAMAS), May, 2013

レジリエンスを表す性質を定義

- **Configuration Trajectory**: some specifications of a particular *system trajectory* S_0, S_1, S_2, …
- Properties on configuration trajectories:
  - –***l*-resistance:** the cost of each state has to be kept under *l*
  - –**<*p,q*>-recoverability:** to recover to a baseline of acceptable quality (< *p*) as quickly and inexpensively as possible
  - –***f*-functionality:** to provide an average degree of quality *f* during the lifetime of the system
  - –***s*-stabilizability:** to avoid high (> *s*) transitional costs
- A system is **<*l,p,q,f,s*>-resilient** if there is a **strategy** whose all **scenarios** admit a **configuration trajectory**, which is *l*-resistant, <*p,q*>-recoverable, *s*-stabilized and *f*-functional.

レジリエンスの諸相

レジリエンスのタクソノミ

1. 何に対して？ – 脅威の種類
2. 何を？ – 守るべきシステム
3. どの局面で？
4. 回復のタイプ

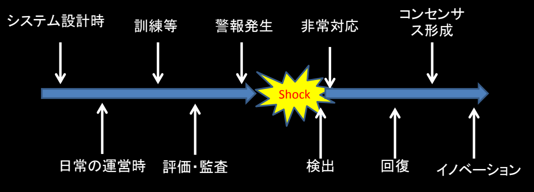
1.何に対して？ – 脅威の種類

- 原因: 自然災害 ⇔ 意図的な攻撃
- 頻度: 頻発 (例:交通事故) ⇔ 極めて稀 (例:巨大隕石の衝突)
- 予測可能性: 予測可能（例:台風の上陸） ⇔ 予測不能（例:巨大地震）
- 継続時間: 瞬間的 (例:落雷) ⇔ 継続的 (例:地球温暖化)
- 要因: 外的要因（自然災害） ⇔ 内的要因（例:金融危機）

2.何を？ – 守るべきシステム

- 対象領域
  - 生物、工学システム、社会インフラ、金融システム、会社組織、コミュニティ、社会全般、…
- 受動的 vs 能動的
  - 自律的(e.g., 生物) ⇔ 管理的 (e.g., 会社)
- 粒度
  - 個人・個体 ⇔ コミュニティ(単一種) ⇔ エコシステム(複数種)
- 目的関数
  - 単純（例:企業 -- 1株あたり利益） ⇔ Complex (例:政府 – 多くの相反するステークホルダ)

3. どの局面で？



4. 回復のタイプ

- 構造的レジリエンス
  - システムの構造も含めて復元する
- 帰納的レジリエンス
  - システムの構造は変化してもよいが、同じ機能を復元する
- 適応的レジリエンス
  - システムの目的も含めて、新たなあり方を模索する

レジリエンス研究の枠組み

1.Type of Shock	Cause	Natural	<==========================>			Intentional
	Frequency	Frequent	<==========================>			Rare
	Anticipation	Predictable	<==========================>			Unknown unknown
	TimeScale	Acute	<==========================>			Chronicle
	Source	External	<==========================>			Internal
2. Target System	Domain	Biological	Engineering	Financial	Legal	Civil Infrastructure
		Organization	Community	Society		
	Passive?	Passive	<==========================>			Active
	Granularity	Individual		Single type		Multiple Types
	Objective	Simple	<==========================>			Complex
3. Phase of resiliency		Design time	Operations	Training	Evaluation	Early warning
		Detection	E. Response	Recovery	Consensus	Innovation
4. Type of resiliency		Structural		Functional		Adaptive

Resilience Research Worksheet

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Tenda Okimoto, Naoto Ikegai, Tony Ribeiro, Katsumi Inoue, Hitoshi Okada and Hiroshi Maruyama. Cyber Security Problem based on Multi-Objective Distributed Constraint Optimization Technique. The 1st Workshop on Systems Resilience (WSR), June, 2013.

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Yoshiki Yamagata and Hajime Seya. Community-based Resilient Electricity Sharing: Optimal Spatial Clustering. The 1st Workshop on Systems Resilience (WSR), June, 2013.

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Hiroshi Maruyama, Kiyoshi Watanabe, Sachiko Yoshihama, Naohiko Uramoto, Yoichi Takehora, and Kazuhiro Minami. ICHIGAN Security - A Security Architecture that Enables Situation-Based Policy Switching. In Proceedings of the 3rd International Workshop on Resilience and IT-Risk in Social Infrastructures (RISI 2013), September, 2013.

Thank You