ISSN 2427-4577

BULLETIN N° 215
ACADÉMIE EUROPEENNE INTERDISCIPLINAIRE DES SCIENCES

INTERDISCIPLINARY EUROPEAN ACADEMY OF SCIENCES

Lundi 9 mai 2017:
à 17 h à la Maison de l'AX, 5 rue Descartes 75005 PARIS

PRÉSENTATION DE TRAVAUX DE NOS COLLÈGUES :

- **Claude MAURY:" *L'intelligence artificielle soumise au regard des philosophes*"**
- **Alain CARDON: " *La génération et l'appréhension des représentations idéelles artificielles et naturelles*"**
- **Jacques PRINTZ : " *Une ingénierie sans fondement : l'information* ?"**
- **Michel GONDRAN: " *Les ondelettes Minplus et les analyses fractales et multifractales*"**

Notre Prochaine séance aura lieu le mardi 12 juin 2017 à 17h
5 rue Descartes 75005 PARIS

Elle aura pour thème

I. Conférence de Luc STEELS, Professeur à l'Institut de Biologie évolutive (UPF-CSIC) de Barcelone/Espagne :
"Comment pouvons nous développer des théories scientifiques relatives à l'origine et à l'évolution des langages"

II. Eventuel Examen de Candidature(s)

Académie Européenne Interdisciplinaire des Sciences
Siège Social : 5 rue Descartes 75005 Paris
http://www.science-inter.com

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Séance du Lundi 9 mai 2017 /Maison de l'AX 17h

La séance est ouverte à 17h **sous la Présidence de Victor MASTRANGELO** et en la présence de nos Collègues Gilbert BELAUBRE, Jean-Louis BOBIN, Alain CARDON, Sylvie DERENNE, Françoise DUTHEIL, Claude ELBAZ, Michel GONDRAN, Irène HERPE-LITWIN, Gérard LEVY, Pierre MARCHAIS, Claude MAURY, Marie-Françoise PASSINI, Jacques PRINTZ, Alain STAHL, Mohand TAZEROUT ,Jean-Pierre TREUIL, .

Etaient excusés :François BEGON, Jean-Pierre BESSIS, Bruno BLONDEL, Michel CABANAC, Juan-Carlos CHACHQUES, Gilles COHEN-TANNOUDJI, Alain CORDIER , Daniel COURGEAU, Ernesto DI MAURO, Jean-Felix DURASTANTI, Vincent FLEURY, Robert FRANCK, Jean -Pierre FRANCOISE, Dominique LAMBERT, Valérie LEFEVRE-SEGUIN, Antoine LONG, Anastassios METAXAS, Alberto OLIVIERO, Edith PERRIER, Pierre PESQUIES, Jean SCHMETS , Michel SPIRO, Jean-Paul TEYSSANDIER , Jean VERDETTI.

Les titres des travaux présentés par nos collègues ont été les suivants:

A. **Claude MAURY:" *L'intelligence artificielle soumise au regard des philosophes*"**
B. **Alain CARDON: " *La génération et l'appréhension des représentations idéelles artificielles et naturelles*"**
C. **Jacques PRINTZ** : **" *Une ingénierie sans fondement : l'information* ?"**
D. **Michel GONDRAN: " *Les ondelettes Minplus et les analyses fractales et multifractales*"**

Notre Collègue Claude MAURY nous avait confié un document complet publié dans le précédent Bulletin n°214 de l'AEIS (avril 2017). Nos Collègues Alain CARDON, Jacques PRINTZ et Michel GONDRAN dont seuls des résumés avaient été publiés nous ont entretemps fourni des documents complets accessibles dans la section documents.

Annonces

I. **Quelques ouvrages papiers relatifs au colloque de 2014 " Systèmes stellaires et planétaires- Conditions d'apparition de la Vie"   -**

– Prix de l'ouvrage :25€ .
– Pour toute commande s'adresser à :

Irène HERPE-LITWIN Secrétaire générale AEIS
39 rue Michel Ange 75016 PARIS
06 07 73 69 75
irene.herpe@science-inter.com

Documents

Pour compléter l'intervention de Claude MAURY nous vous proposons: de lire sur le site http://vie.jill-jenn.net/2016/02/05/deep-learning-au-college-de-france/ un article intitulé "Deep Learning au Collège de France"

Nos collègues Alain CARDON, Jacques PRINTZ et Michel GONDRAN nous ont par ailleurs fourni les documents suivants:

p.06 : Article d'Alain CARDON " Génération et appréhension des Représentations idéelles et artificielles"

p.10 article de Jacques PRINTZ intitulé " L'ingénierie de l'information n'est-elle qu'un vaste bricolage ? Où est passée la science qui fonde cette ingénierie ? "

p. 24 article de Michel GONDRAN " Ondelettes Minplus: Analyses fractales et Multifractales"

Pour préparer la conférence du Pr Luc STEELS nous vous proposons :

p. 50 : Un article de Luc STEELS "Agent-based models for the emergence and evolution of grammar" publié dans Phil. Trans. R. Soc. B 371: 20150447. http://dx.doi.org/10.1098/rstb.2015.0447

Génération et appréhension des

représentations idéelles artificielles et naturelles

Alain Cardon AEIS – 9 Mai 2017

La notion de représentation

- Une représentation est ce qui est conçu et perçu comme expression mentale à propos de quelque chose.

- C'est l'appréhension et la sensation éprouvée de quelque chose de naturel venant des sens ou de totalement symbolique et abstrait, comme de la signification langagière ou conceptuelle ou bien une union des deux.

Le système qui génère les représentations

- C'est un **système de systèmes auto-organisateur** sur un substrat formé d'éléments ponctuels lançant de la signification par agrégations.

- Son architecture est basée sur l'activation de systèmes de systèmes dynamiques coactifs au niveau énergique et informationnel à de multiples échelles : **réseaux de systèmes informationnels.**

- Le système produit des formes **émergentes**, **spatiales**, géométriques, sur le substrat (agrégats de neurones ou d'agents logiciels) et qui sont les représentations.

Deux caractères de l'architecture

- Il y a deux caractères architecturaux particuliers :

1. Des **systèmes dynamiques** très coactifs, formant de multiples organisations locales sur les éléments du substrat qui génèrent des **formes** dotées de signification par leurs unions coactives : notion de formes signifiantes.
2. Des **éléments de contrôle (régulateurs)** incitent les systèmes dynamiques à s'activer et à se coactiver et surtout à s'unir en agrégats dans des formes constituant l'ensemble général qui sera mis à appréhension : notion de réseaux de contrôle.

Le paysage mental

- Des éléments de contrôle et des agrégats de systèmes dynamiques dotés de signification s'activent à partir d'une incitation, d'une visée, et génèrent un construit d'agrégats dynamiques qui a de multiples caractères et qui est le **paysage mental actif**.
- Les éléments du paysage expriment géométriquement trois caractères : de la signification réaliste, des formes abstraites, des sensations.
- La représentation éprouvée est une émergence construite et sélectionnée dans le paysage mental.

Processus de génération d'une pensée

1. Une visée choisie par le régulateur méta ou imposée par les sens.
2. La sélection de formes adaptées activées dans le paysage mental.
3. La construction de la représentation par les régulateurs et son émergence avec son appréhension (pas de détachement !).
4. Modification du paysage et mémorisation.
5. Pensée suivante par continuité dans le paysage mental modifié.

Paysage mental

- C'est l'ensemble bien organisé des systèmes dynamiques coactifs ayant des formes signifiantes et qui est structuré en domaines typologiques :

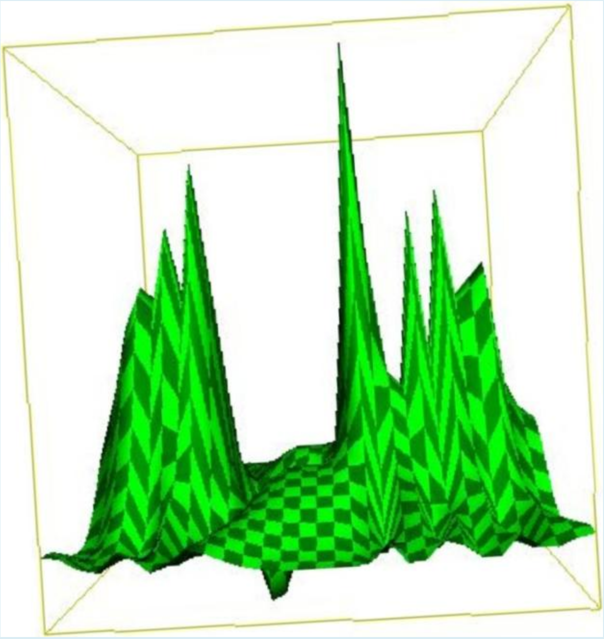
1. Les parties exprimant les formes réelles et sensibles venant des sens.
2. Les parties exprimant les connaissances abstraites et symboliques.
3. Les parties exprimant les dénotations langagières.

4. Les parties mémorielles exprimant le dynamisme du vécu courant.

5. Les parties exprimant les tendances dominantes du moment qui caractérisent et altèrent tout le paysage.

6. Des parties éventuellement perturbatrices et autonomes (contrôle par des **attracteurs**).

- Le paysage est construit et reconstruit sans cesse sous l'action des éléments de contrôle dont celui générant l'appréhension (**régulateurs**) et sous l'effet de la mémoire des paysages mentaux.



Les caractères de la représentation

- La représentation est une forme de formes dynamiques actives, construite et manipulée qui émerge dans le paysage mental.

- Cette forme à des caractères plus importants que d'autres, des caractères associés formant des domaines dynamiques et certains caractères antagonistes qui ne seront pas exprimés.

- Elle est un construit dynamique amplifiant toujours certains caractères (*notion de sup demi-treillis*), ce qui va faire l'émergence appréhendée et générer la sensation.

La sensation de penser

- Générer une pensée est construire effectivement, dans tous les cas, une représentation dans le paysage mental courant.
- La construction est l'action multi-échelle d'éléments de contrôle (les régulateurs) et de l'action coactivite entre les formes systémiques.
- Cette action est énergétique et surtout informationnelle et elle est ainsi ressentie comme telle, comme un **acte mental interne continu et variable**.

Conclusion

- Approche systématiquement opposée au courant naturaliste réductionniste et différente des analyses d'observation par imagerie neuronale d'états actifs, car se basant sur une **architecture dynamique** qui produit l**es émergences de représentations** dans des **systèmes de systèmes coactifs** conduits avec des éléments **régulateurs gérant les informations** .

L'ingénierie de l'information n'est-elle qu'un vaste bricolage ?

⌘⌘⌘

☞ Où est passée la science qui fonde cette ingénierie ?

J.Printz, Professeur Émérite du Cnam

Réunion AEIS du mardi 9 mai

Une leçon inaugurale, *Problèmes futurs du génie logiciel*, 20 ans après ...

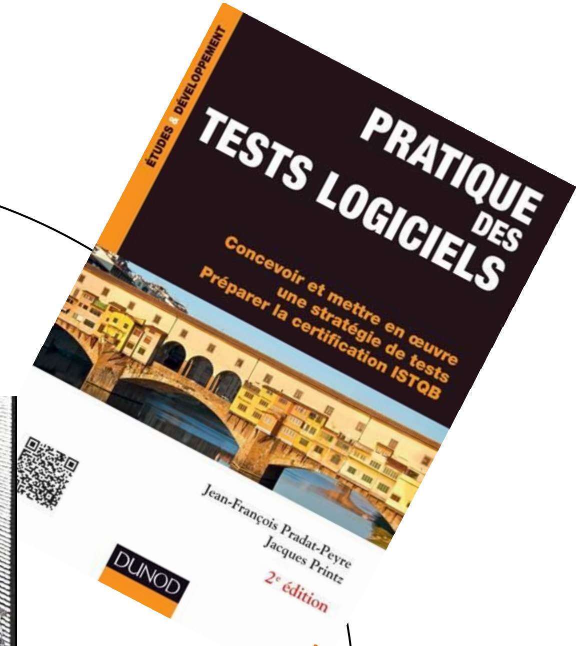
Sous un double parrainage, présidée par Maurice Nivat, en Mai 1995 :

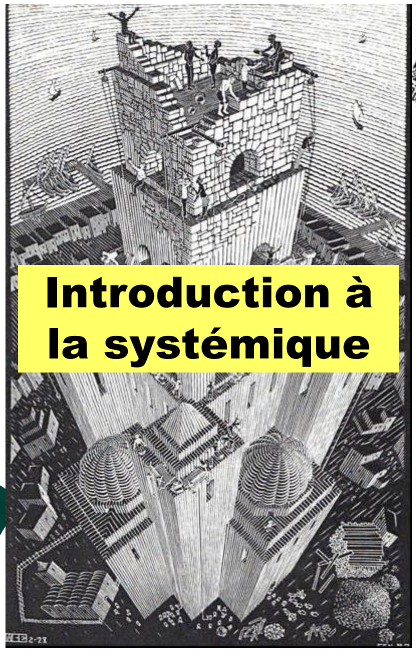
1) En effet, pour pouvoir examiner avec fruits les principes d'une science, il faut être familiarisé avec ses théories particulières; seul, l'architecte qui connaît à fond, dans tous leurs détails, les diverses destinations d'un bâtiment, sera capable d'en poser sûrement les fondations.
☞ David Hilbert, *Les 23 Problèmes* : VI, *Le traitement mathématique des axiomes de la physique*.

2) The great progress in every science came when, in the study of problems which were modest as compared with ultimate aims, methods were developed which could be extended further and further.
...
The sound procedure is to obtain first utmost precision and mastery in a limited field, and then to proceed to another, some that wider, and so on.
...
The experience of more advanced sciences indicates that impatience merely delays progress, including that of treatment of the «burning» questions.
There is no reason to assume the existence of shortcuts.
☞ John von Neumann, *Theory of Games and Economic Behavior.*

5 points :

- **Le Génie Logiciel et sa problématique**
- **L'erreur humaine**
- **La sûreté de fonctionnement du logiciel**
- **Les nouvelles architectures**
- **Quelques implications sociales en conclusion**



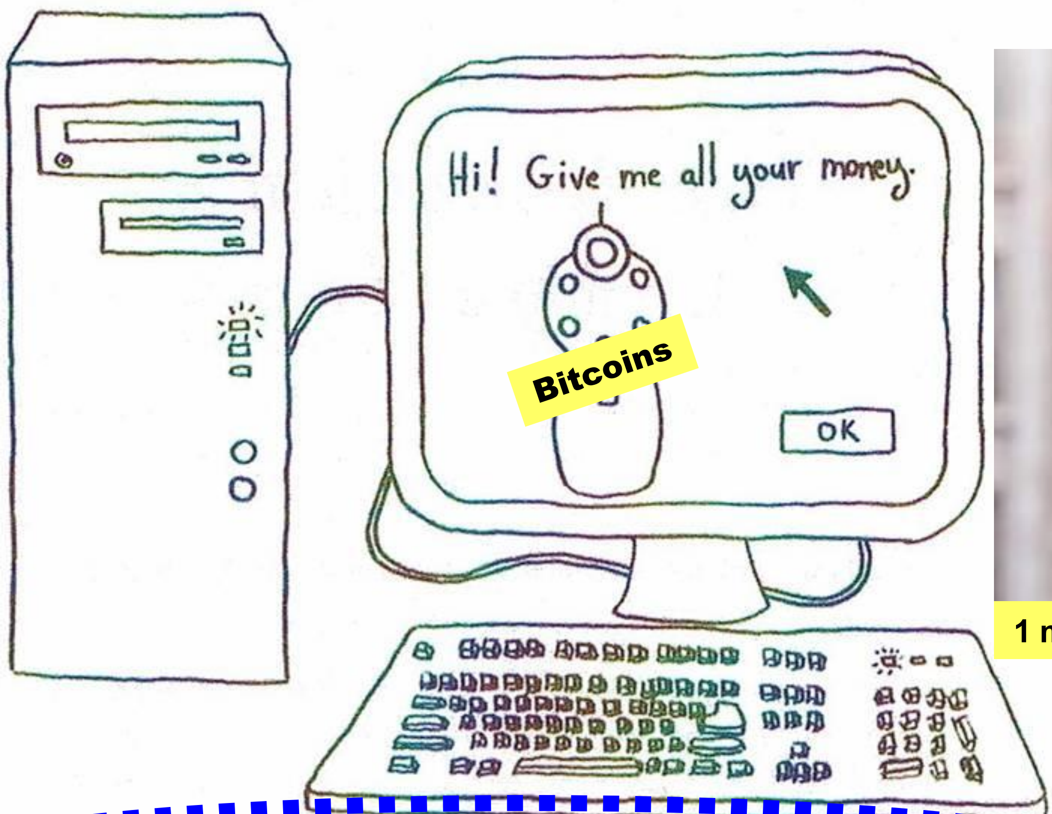


Introduction à la systémique

Éclaircissements

- **Ingénierie et/ou bricolage – Où est la frontière ?**
- **Peut-on parler d'ingénierie et/ou de qualité de l'information ?**
  - ☞ **Ingénierie de QUOI ?**
- **En QUOI, et par QUOI une ingénierie est-elle fondée ?**
  - Quelle est sa « physique », c'est-à-dire le phénomène qu'elle étudie et organise ?
  - Cette « physique » est-elle mathématisable ?

Interrogations initiales → le Phénomène



Computation is based on an enormous tower of functionalities.

Source : R.Laughlin, *A different universe*
(Reinventing physics from the bottom down)

1 millions de fois la performance de Whirlwind

- **Transistors**: Up to 8 cores: **2.60** billion, Up to 12 cores: **3.84** billion, Up to 18 cores: **5.69** billion
- **Die size**: Up to 8 cores: 354 mm², Up to 12 cores: 492 mm², Up to 18 cores: 662 mm²
- ☞ Environ 8 millions de transistors/mm²

Pourquoi/Comment ça marche ?!

On regarde d'un peu plus près …

Opérations
C /Créer
R /Rechercher
U /Modifier
D /Effacer
E /Exécuter

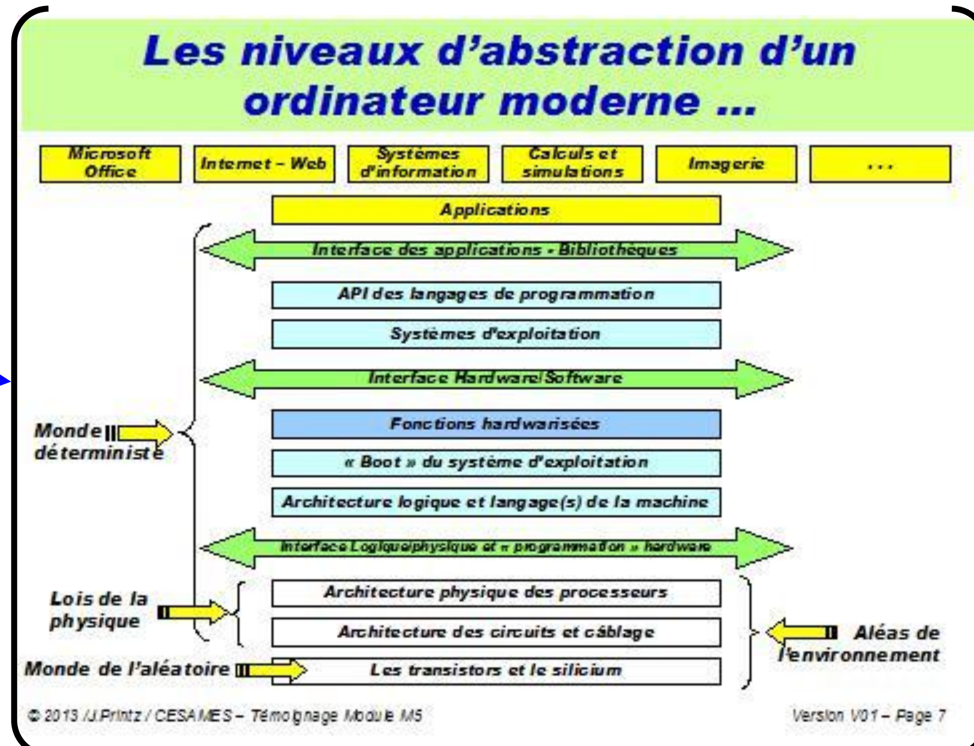
Interactions

Infrastructures et ressources informationnelles

Mise à disposition d'une bibliothèque de programmes d'au minimum 20 à 30 millions d'instructions source, soit environ 100 millions d'instructions machine

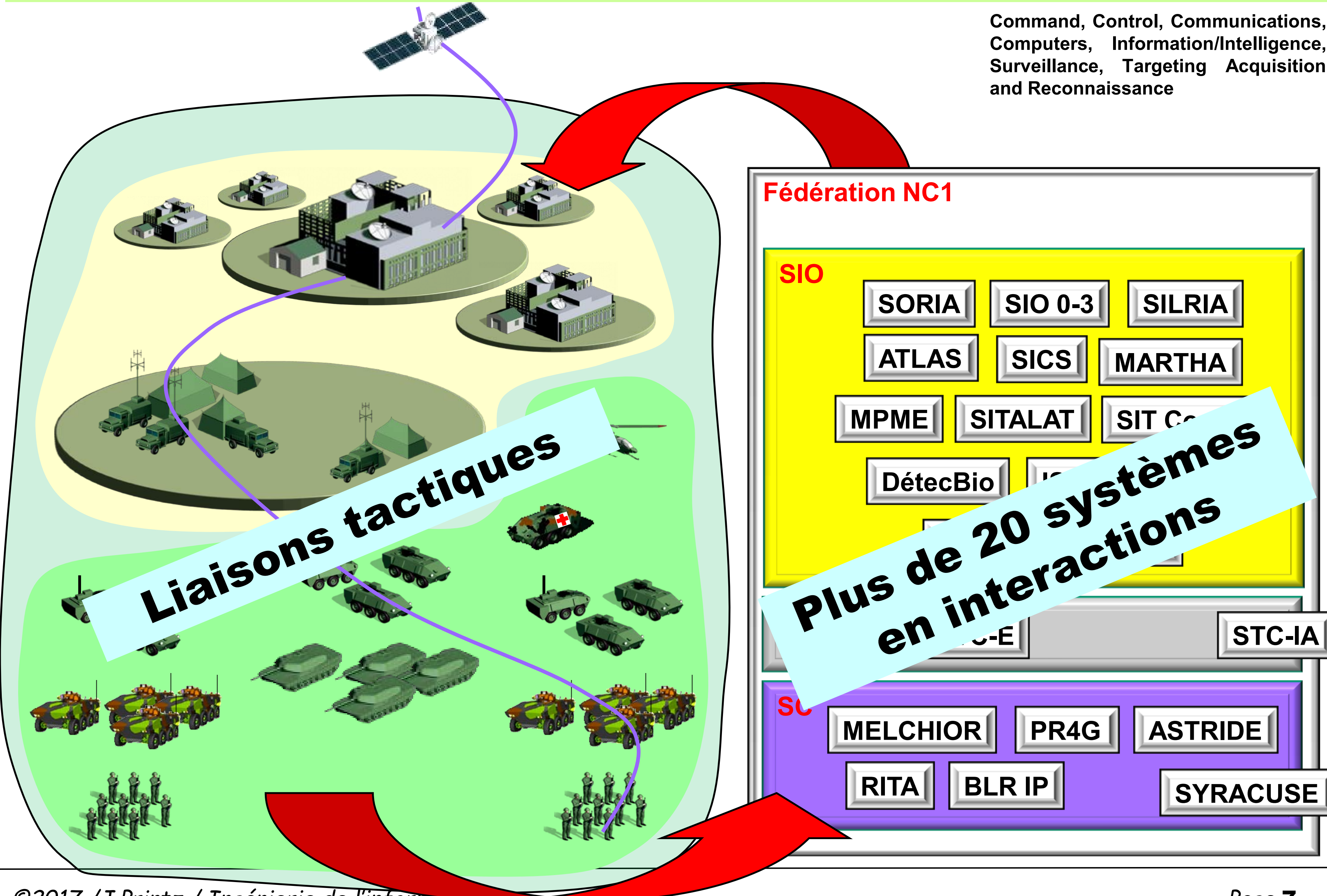
La face cachée de l'iceberg

2 « miracles » :
- **l'intégration des composants**
- **l'architecture logicielle**



→ Systèmes de Systèmes – C4ISTAR

Command, Control, Communications, Computers, Information/Intelligence, Surveillance, Targeting Acquisition and Reconnaissance

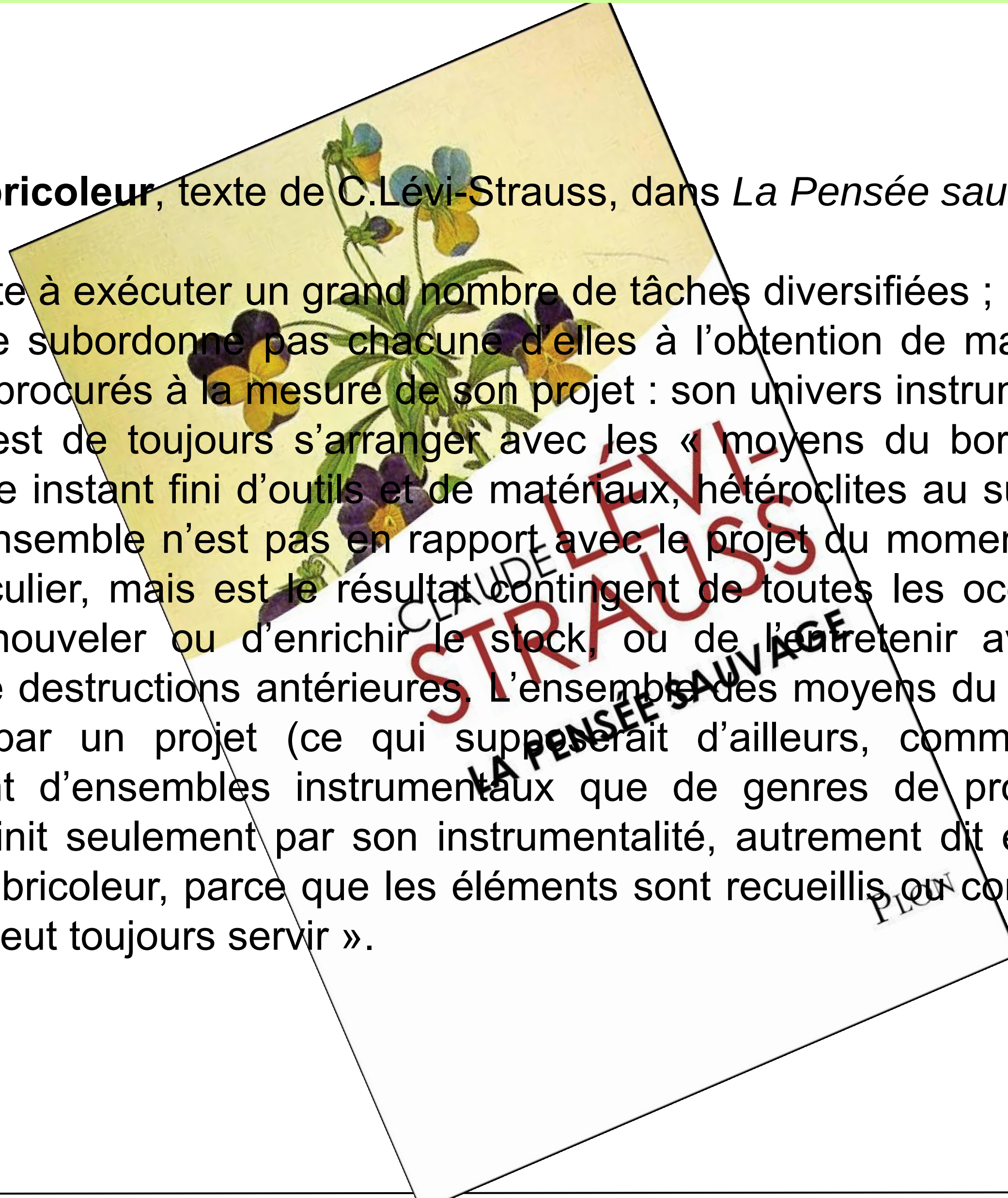


Survivre aux erreurs …

S'adapter aux évolutions ou périr …

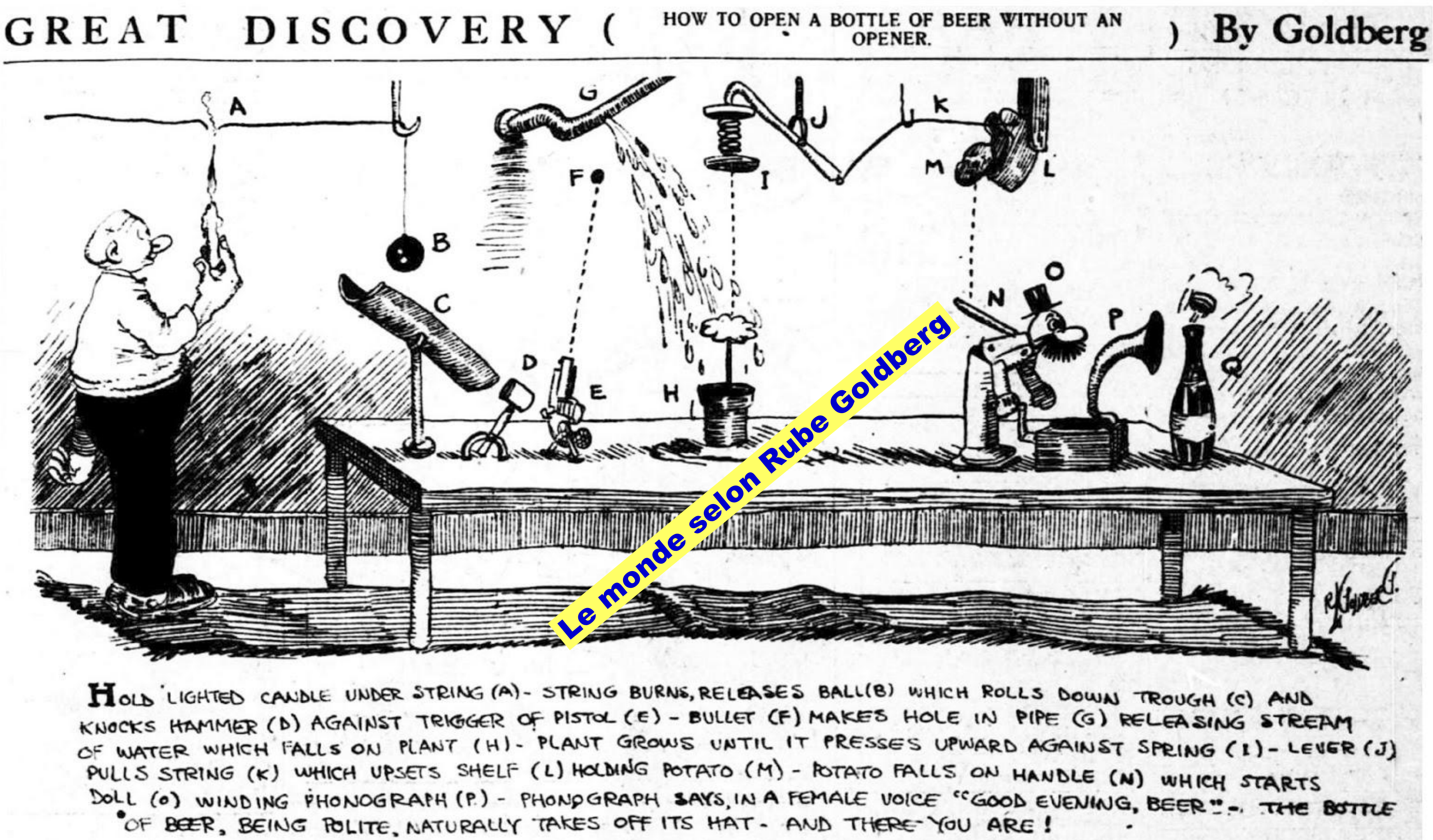
- **Dans un SdS, chacun des systèmes autonomes doit survivre à :**
  - ➔ **Ses propres erreurs**
    - ✓ *C'est classique, mais c'est difficile*
  - ➔ **Celles des autres systèmes qui peuvent l'infecter**
    - ✓ *C'est nouveau, et c'est très difficile*
- **Dans UN système, il y a par définition un point de contrôle central – C'est impossible dans un SdS**
  - ☞ **Rôle pivot du modèle/pivot d'échanges**

Bricolage ou … ?



L'ingénieur et le bricoleur, texte de C.Lévi-Strauss, dans *La Pensée sauvage*, Plon, p27.
[…]
Le bricoleur est apte à exécuter un grand nombre de tâches diversifiées ; mais, à la différence de l'ingénieur, il ne subordonne pas chacune d'elles à l'obtention de matières premières et d'outils, conçus et procurés à la mesure de son projet : son univers instrumental est clos, et la règle de son jeu est de toujours s'arranger avec les « moyens du bord », c'est-à-dire un ensemble à chaque instant fini d'outils et de matériaux, hétéroclites au surplus, parce que la composition de l'ensemble n'est pas en rapport avec le projet du moment, ni d'ailleurs avec aucun projet particulier, mais est le résultat contingent de toutes les occasions qui se sont présentées de renouveler ou d'enrichir le stock, ou de l'entretenir avec les résidus de constructions et de destructions antérieures. L'ensemble des moyens du bricoleur n'est donc pas définissable par un projet (ce qui supposerait d'ailleurs, comme chez l'ingénieur, l'existence d'autant d'ensembles instrumentaux que de genres de projets, au moins en théorie) ; il se définit seulement par son instrumentalité, autrement dit et pour employer le langage même du bricoleur, parce que les éléments sont recueillis ou conservés en vertu du principe que « ça peut toujours servir ».

Ingénierie et/ou Bricolage



Comment comparer ? Analogies ? ...

- **Analogies/comparaisons liées à la taille exprimée en Lignes de Code Source** [LCS] **écrites par les programmeurs, aux normes de l'édition**
  - Word → Environ 250.000 LCS ➔ **15 livres** de 400 pages
  - Un OS comme GCOS7 ➔ **250 livres**
  - Une fédération de systèmes [SdS] ➔ **2.500 livres**
- **Analogies/comparaisons liées au coût de développement exprimé en <u>Heures ouvrées</u>** [ho]
  - Le programmeur « moyen » produit environ **4.000** LCS validées, testées et intégrées [soit environ 80 à 100 pages de texte] **par an** [pour 1.700-1.800 ho]
  - Un OS comme GCOS7 ➔ Environ **6 millions ho**
  - Un SdS type défense ➔ Environ **100 millions ho** [en incluant un facteur d'échec sur lequel on a des statistiques précises]

Tour Khalifa de Dubaï

22 millions d'heures de travail

Dont seulement 15-20% d'heures véritablement qualifiées [Bureau d'études]

De quoi l'ingénierie de l'information est-elle le nom ?
Et d'abord, qu'est-ce que l'information ?

Pour les informaticiens, la réponse ne fait guère de doute :

☞ **Ce sont les textes de toute nature, y compris ceux en langage naturel, qu'ils manipulent pour communiquer, pour réaliser le ou les systèmes d'information qui répondent aux exigences de leurs usagers et commanditaires.**

➔ **Mais pour un biologiste, un physicien, un mathématicien, un … ???**

☞ **L'élaboration de ces textes qui sont des compromis a un coût que l'on peut dimensionner comme une énergie.**

☞ **Il n'y a pas de coopération possible sans communication entre les acteurs qui agissent – cela implique des conventions → Un référentiel**

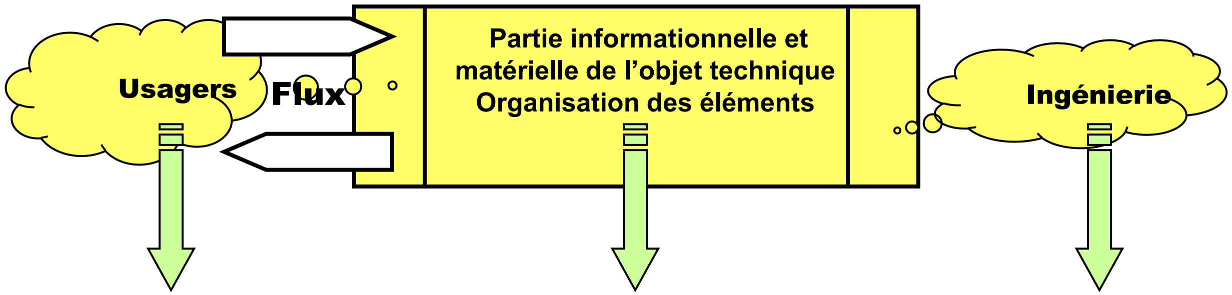
Peut-on parler de complexité de l'information ? Et si oui, comment ?

En se coulant dans une logique textuelle propre aux langages utilisés par les informaticiens on peut faire apparaître des paramètres d'organisation de ces différents textes comme cela existe dans nos langues naturelles → Dimensions de la complexité :

- **Richesse du vocabulaire utilisé**
- **Grammaire, et pour la reconnaissance → Automates de reconnaissance**
- **Style et organisation de documents → Tables de matières, thesaurus, liens hypertexte, …**
- **Architecture sémantique via différents systèmes d'indexation, de balisage → Cf. des langages comme SGML/HTML**
- **Volume/taille des tests de validation/vérification**

Les trois complexités – Intrication

☞ Faire du fiable avec du NON fiable



Complexité des interactions des usagers avec le système Compétences requises par le contrat de service	**Complexité des interactions des éléments constitutifs du système pour satisfaire le contrat de service**	**Complexité des interactions des acteurs de l'ingénierie pour satisfaire le contrat de service**
Complexité des usages	**Complexité structurelle de la « machine »**	**Complexité projet de l'ingénierie**

Trois architectures cohérentes, mais :

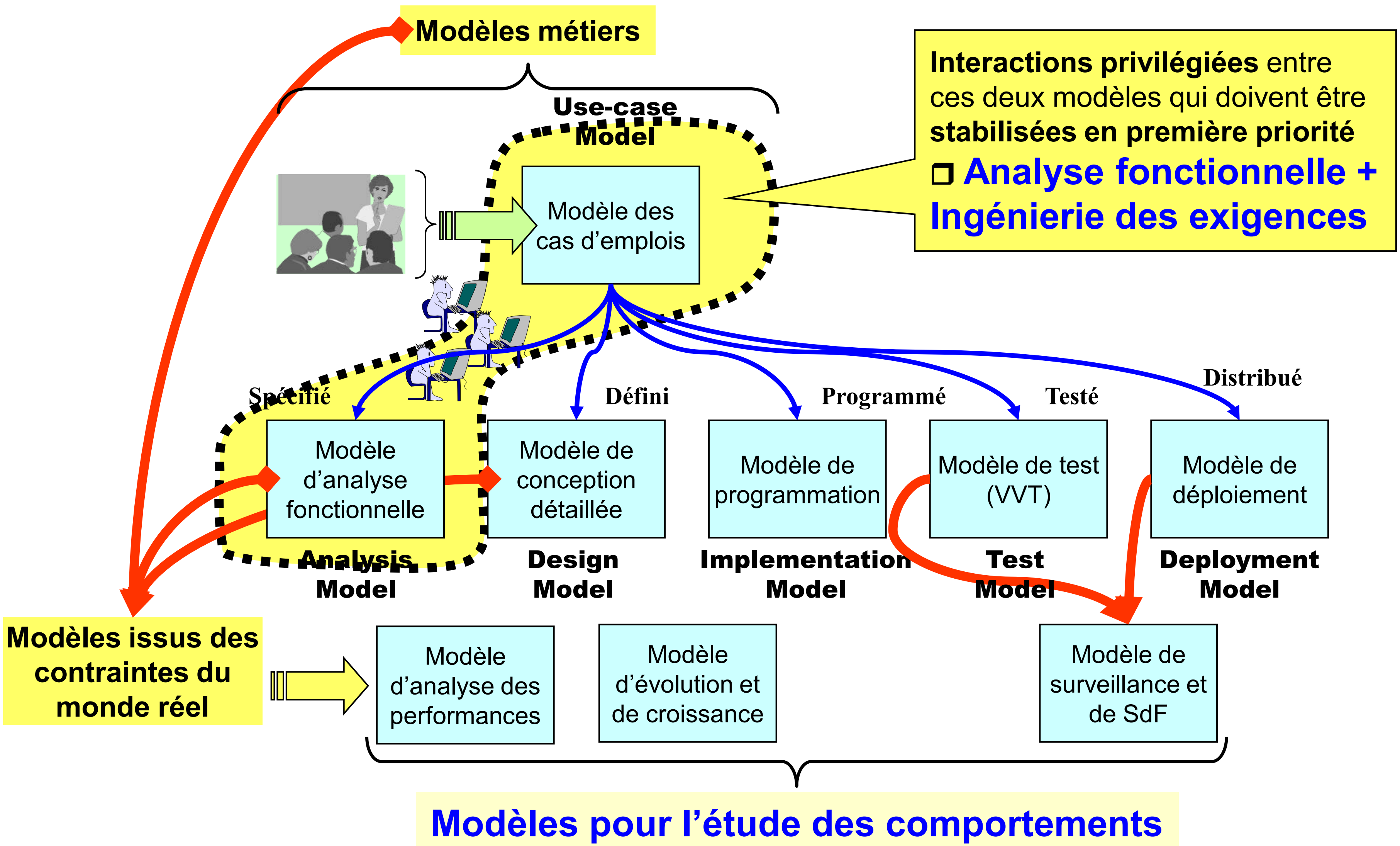
→ Taux d'erreurs des usagers	**→ Taux de pannes de la machine**	**→ Taux d'erreurs de l'ingénierie**
Rapports d'anomalies Demandes d'évolutions fonctionnelles, adaptations, optimisations, …	Erreurs résiduelles Évolution et usure des équipements et des ressources, …	Évolution des méthodes et des outils Renouvellement des équipes et des organisations, …

Omniprésence du facteur humain

- **Dans l'ingénierie de l'information il est impossible d'éliminer le facteur humain**
  ☞ **C'est une différence radicale avec l'ingénierie classique où tout a été construit pour éliminer le facteur humain**

- **Les lois de la physique où de la chimie sont « objectives » – Dans la communication, au sens de Shannon, tout ce qui traite du sens et de l'interprétation a été volontairement exclu – Un bon langage de programmation doit être "*Context free*" pour éviter toute ambiguïté et/ou subjectivité**
  ☞ **C'est l'organisation, la structure de l'information et les relations qui vont porter le sens**

Modèles – Interactions entre modèles



➘ Cf. livre J.Printz, *Écosystème des projets informatiques*

Une ingénierie de l'erreur à inventer

☞ ***Richard W.Hamming*** : "Most bodies of knowledge give errors a secondary role, and recognize their existence only in the later stages of design. **Both coding and information theory, however, give a central role to errors (noise) and are therefore of special interest, since in real-life noise is everywhere**", que l'on peut traduire par « La plupart des domaines de connaissances donnent aux erreurs un rôle secondaire, et reconnaissent leur existence seulement dans les dernières étapes de la conception. La théorie des codes et la théorie de l'information donnent toutes deux une place centrale aux erreurs (bruit) et pour cette raison présentent un intérêt particulier, car dans la vie réelle le bruit est partout »
➔ on ne saurait mieux dire !

- **La problématique de l'erreur humaine est un sujet « ouvert », particulièrement difficile …**
  La nature des erreurs humaines peut être
- **➔ Individuelle**
  - ✓ Performance et capacité de l'individu
- **➔ Collective**
  - ✓ Caractéristique des équipes et/ou organisations qui relèvent de la sociodynamique
    - ☞ Comment compenser les biais cognitifs et le mimétisme …

Une remarque préliminaire …

↳ **La raison d'être fondamentale de l'ingénierie est de <u>combattre les erreurs</u>, d'où qu'elles viennent :**

- Des matériaux utilisés pour construire les systèmes
  - ➘ **Matériaux du monde réel « physique »**, matériels dont on connaît certaines propriétés grâce à la science des matériaux
  - ➘ **Matériaux du monde « virtuel » ☞ l'information**, immatériels produits par l'intelligence humaine [le Monde 3 de K.Popper] dont on découvre progressivement qu'ils sont un monde en soi, avec des « lois » qui leur sont propres
    ➔ les programmes et la programmation, les modèles, au sens large
- Des concepteurs, développeurs et exploitants des systèmes
  - ➘ C'est-à-dire le cœur de l'ingénierie elle-même, productrice d'erreurs informationnelles
- Des usagers qui interagissent avec les systèmes, et qui font eux-mêmes des erreurs

<u>Pour que les usagers aient confiance</u>

Quelques chiffres

- **Pour un opérateur humain, dans des conditions « normales », le taux d'erreur** [une action erronée, ou inappropriée] **moyen est de l'ordre de 5 à 10 erreurs par heure d'activité effective**

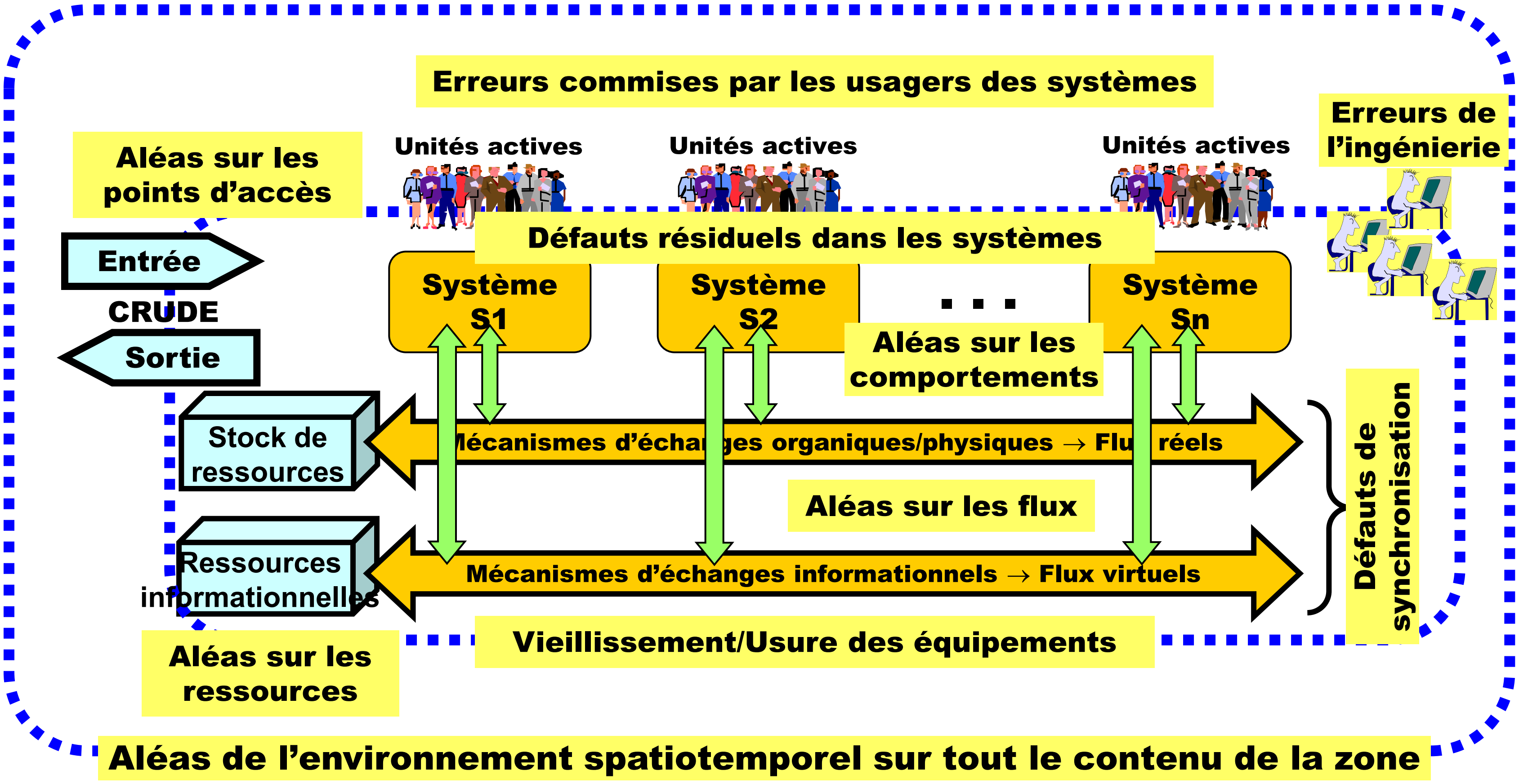
  ➔ Mais ce taux augmente fortement en cas de stress ☞ Très variable selon les individus

- **Pour un grand projet système** [cf. ma présentation à l'Académie des Sciences]**, 36.000 FT ont été répertoriés et traités, pour un volume de code livré de ≈3,6 millions de LS, soit ≈1 FT/100 LS**

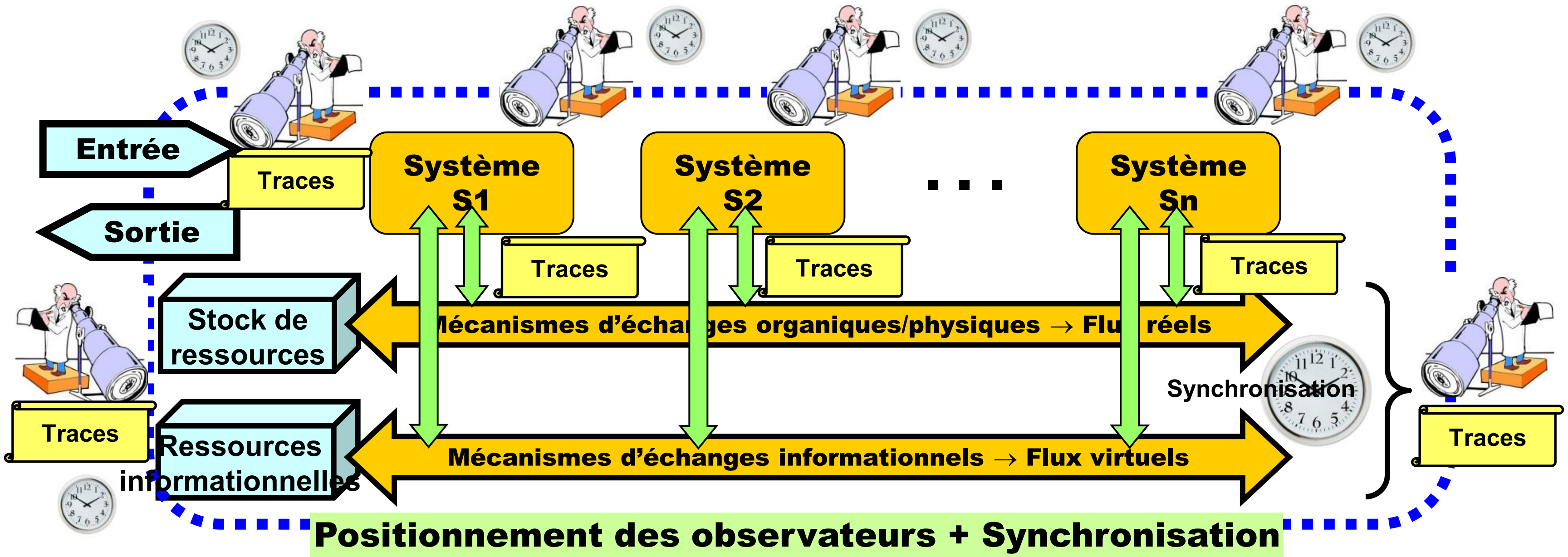
  ☞1 anomalie toutes les 2 pages de texte

- **Les logiciels à bord de la navette spatiale ≈0,1 Err/KLS après livraison** [≈1 erreur résiduelle toutes les 200 pages]

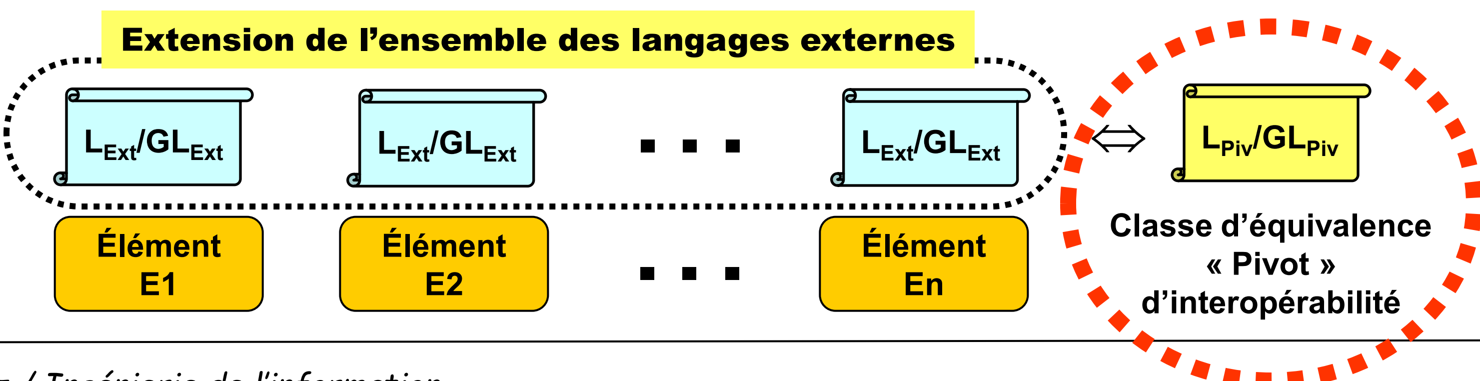
SdS – Aléas, défauts, erreurs, …



SdS – Observation

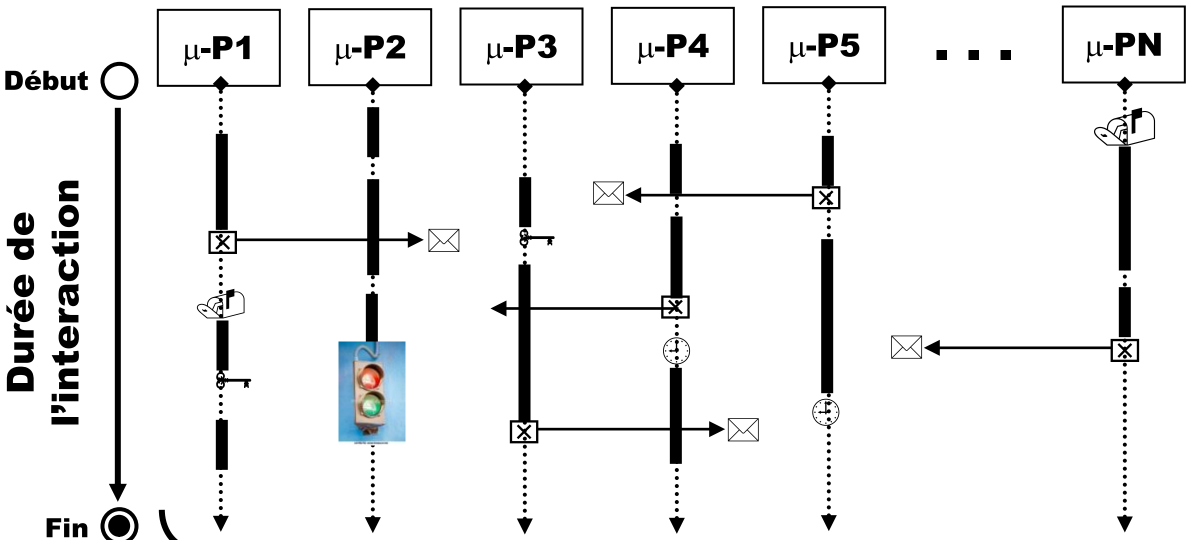


☞ **Rôle crucial de la structure « pivot » dans l'économie générale du SdS**



SdS – Gérer et maîtriser le flots du *Parallélismes* et la *Synchronisation*

☞ **Des milliers de *threads* [modules] qui coopèrent**



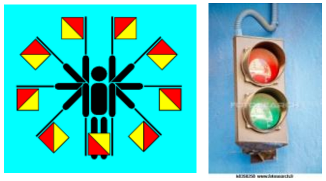
***N* [Micro]processeurs physiques**
[mais beaucoup plus de processeurs logiques avec la **virtualisation des ressources**]

Horloges :

Verrous et clés :

Mécanismes de synchronisation et/ou de coopération du système S :

Sémaphores et/ou feux de croisements :



Boites aux lettres :

Priorités :

La combinatoire est cachée dans les interactions dynamiques nécessaires à la coopération

Coopérer pour survivre à la complexité d'un monde interconnecté

- **La complexité / intrication des systèmes fait qu'il est impossible de tout vérifier « à l'ancienne »**
- **Nous sommes coresponsables de la sécurité de nos systèmes ☞ Éthique et professionnalisme**
  - La métaphore des gardiens [John von Neumann] ☞ ***Quis custodiet ipsos custodes*** [Qui garde les gardiens ?]

☞ Si nous n'organisons pas la complexité, la complexité nous détruira

> ☞ ***We can specify only the human qualities required: patience, flexibility, intelligence***
>
> [in ***Can we survive technology***, John von Neumann, Fortune, June 1955]

Ondelettes Minplus et analyses fractales et multifractales

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Plan

Analyse Minplus : Remplacer le produit scalaire L^2

$$\langle f, g\rangle = \int_{x\in X} f(x)g(x)dx$$

par le **produit scalaire Minplus** :

$$\langle f, g\rangle_{(\min,+)} = \inf_{x\in X}\{f(x)+g(x)\}.$$

Remplacer les réels $(\mathbb{R}, +, \times)$ par le dioïde $(\mathbb{R}\cup\{+\infty\}, \min, +)$

Le produit scalaire Minplus est distributif pour min :

$$\langle f, \min\{g_1, g_2\}\rangle_{(\min,+)} = \min\{\langle f, g_1\rangle_{(\min,+)}, \langle f, g_2\rangle_{(\min,+)}\}$$

distribution non linéaire : existance similaire à la distribution Dirac :

$$\delta_{(\min,+)}(\mathbf{x}) = \{0 \text{ if } \mathbf{x} = \mathbf{0}, +\infty \text{ else}\}$$

$$\langle \delta_{(\min,+)}, f\rangle_{(\min,+)} = \min_{x\in X}\{\delta_{(\min,+)}(x) + f(x)\} = f(\mathbf{0}).$$

Il existe en mécanique classique un analogue de l'intégrale de chemin de Feynman :

c'est **l'intégrale de chemin Minplus** qui relie l'action d'Hamilton-Jacobi $S(\mathbf{x},t)$ à l'action classique d'Euler-Lagrange $S_{cl}(\mathbf{x},t;\mathbf{x}_0)$ par l'équation :

$$S(\mathbf{x},t)=\min_{\mathbf{x}_0}(S_0\left(\mathbf{x}_0\right)+S_{cl}(\mathbf{x},t;\mathbf{x}_0))$$

où le minimum est pris sur l'ensemble des positions initiales $\mathbf{x}_0$ et où $S_0(\mathbf{x})$ est l'action d'Hamilton-Jacobi à l'instant initial.

c'est une intégrale dans l'analyse Minplus

Ondelettes Minplus : remplacer les ondelettes classiques

$$T_f(a,b) = a^{-n} \int_{-\infty}^{+\infty} f(x)\Psi\Big(\frac{x-b}{a}\Big)dx,$$

définies pour tout $f : \mathbb{R}^n \to \overline{\mathbb{R}}$ et pour tout $a \in \mathbb{R}^+$ et $b \in \mathbb{R}^n$ par **les enveloppes inférieures** :

$$T_f^-(a,b) = \inf_{x \in \mathbb{R}^n} \Big\{ f(x) + h\Big(\frac{x-b}{a}\Big) \Big\}, \qquad (1)$$

où h est la fonction analysante prise parmi :

$$h_\alpha(x) = \frac{1}{\alpha}|x|^\alpha \text{ with } \alpha > 1 \text{ and } h_\infty(x) = \{0 \text{ if } |x| < 1, +\infty \text{ else}\}.$$

Borne inférieure et reconstruction

$T_f^-(a,x) \leq f(x)$ pour tout $a > 0$ et $f(x) = \sup_{a \in \mathbb{R}^+} T_f^-(a,x)$

On définit aussi les enveloppes supérieures :

$$T_f^+(a,b) = \sup_{x\in\mathbb{R}^n} \left\{ f(x) - h\Big(\frac{x-b}{a}\Big) \right\}. \qquad (2)$$

avec la reconstruction $f(x) = \inf_{a\in\mathbb{R}^+} T_f^+(a,x)$.

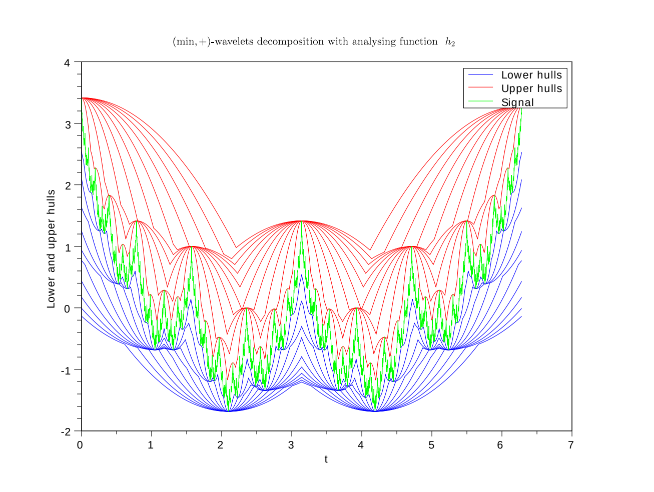
Pour chaque fonction analysante, on a :

$$T_f^-(a,x) \leq f_*(x) \leq f(x) \leq f^*(x) \leq T_f^+(a,x), \qquad (3)$$

avec $T_f^-(a,x)$ (resp. $T_f^+(a,x)$) décroissantes avec l'échelle a (resp.croissante), convergeant vers $f_*(x)$ (resp. $f^*(x)$), la fermeture sci de f (resp. scs) quand l'échelle a tend vers 0.

Ondelettes Minplus définies par les couples $\{T_f^-(a,x), T_f^+(a,x)\}$

Ondelettes h_2 de la fonction de Weierstrass



Definition

Pour tout a, la a-oscillation de f est définie :

$$\Delta T_f(a,x) = T_f^+(a,x) - T_f^-(a,x). \quad (4)$$

Pour h_∞, $T_f^+(a,\mathbf{x}) = \sup_{|\mathbf{x}-\mathbf{y}|\leq a} f(\mathbf{y})$, $T_f^-(a,\mathbf{x}) = \inf_{|\mathbf{x}-\mathbf{y}|\leq a} f(\mathbf{y})$ and $\Delta T_f(a,\mathbf{x}) = \sup_{|\mathbf{x}-\mathbf{y}|\leq a} f(\mathbf{y}) - \inf_{|\mathbf{x}-\mathbf{y}|\leq a} f(\mathbf{y})$ correspond à la a-oscillation défini à une dimension par Tricot : : $\mathrm{osc}_a f(x) = \sup_{y,z\in[x-a,x+a]}[f(y) - f(z)]$.

la a-oscillation va servir

- à étudier les contours
- à étudier la fractalité et la multifractalité

Ondelettes Minplus : Lena

Théorème sur les fonctions de Hölder

La fonction f est Höldérienne avec l'exposant H, $0 < H \leq 1$, ssi il exite une constante K telle que :

$$|f(x) - f(y)| \leq K|x - y|^H \quad \forall\, x, y \in \mathbb{R}^n. \tag{5}$$

Théorème

La fonction f est Höldérienne avec l'exposant H, $0 < H \leq 1$, ssi il exite une constante C telle que :

$$\Delta T_f(a, x) \leq C a^H \qquad si \;\; h = h_\infty, \tag{6}$$

$$\Delta T_f(a, x) \leq C a^{\frac{\alpha H}{\alpha - H}} \qquad si \;\; h = h_\alpha \;\; et \;\; \alpha > 1. \tag{7}$$

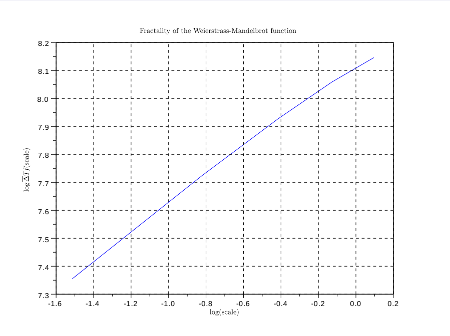
Les fonctions de Weierstrass sur $[0, 2\pi]$

$$W(t) = \sum_{m=0}^{\infty} (\omega^{-H})^m cos(\omega^m t + \varphi_m), \tag{8}$$

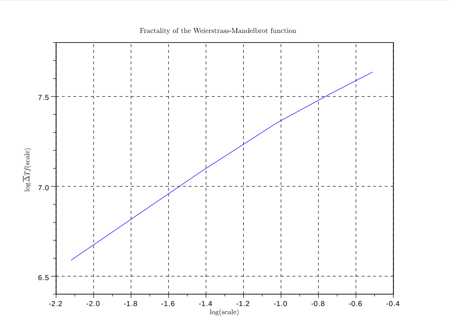
avec $\omega^H > 1$ et $\{\varphi_m\}_{m \geq 0}$ constant où aléatoire. Ces fonctions sont Höldériennes avec exposant H et dimension fractale D=2-H.

On calcule pour toutes les échelles $s = k \cdot \mathrm{scale}_{\text{min}}$ avec k entier de 1 à 10 et $\mathrm{scale}_{\text{min}} = 10^{-2}$, la fonction suivante pour h_2 et h_∞

$$\overline{\Delta T}_f(s) = \int_{\mathcal{T}} \Delta T_f(s,t) dt.$$



Logarithm of $\overline{\Delta T}_{WM}(s)$ according to scale logarithm with h_∞ decomposition of the Weierstrass-Mandelbrot function, $H = \frac{1}{2}$, $\omega = 2$. The slope is obtained with mean of linear regression and its value is 0.496. The theoretical value is $\frac{1}{2}$. That is a relative error of 0.5%.



Logarithm of $\overline{\Delta T}_{WM}(s)$ according to scale logarithm with h_2 decomposition of the Weierstrass-Mandelbrot function, $H = \frac{1}{2}$, $\omega = 2$. The slope is obtained with mean of linear regression and its value is 0.655. The theoretical value is $\frac{2}{3}$. That is a relative error of 1.8%.

Theoretical Hölder exponent H Theoretical slope	$\frac{1}{4} = 0.250$ $\frac{1}{4} = 0.250$	$= 0.500$ $= 0.500$
Numerical Hölder exponent H Numerical slope	0.253 0.253	0.507 0.507
Slope relative error (%)	1.2	1.4

Table : Numerical results for random phase Weierstrass function with $\omega = 2$ and Minplus-wavelets decomposition performed with h_∞.

Theoretical Hölder exponent H	$\frac{1}{4} = 0.250$	$= 0.500$
Theoretical slope	$\frac{2}{7} \simeq 0.286$	$\frac{2}{3} \simeq 0.667$
Numerical Hölder exponent H	0.246	0.497
Numerical slope	0.280	0.661
Slope relative error (%)	2.0	0.9

Table : Numerical results for random phase Weierstrass function with $\omega = 2$ and Minplus-wavelets decomposition performed with h_2.

Analyse multifractale : fonction d'échelle $\xi_f(p)$ et spectre des singularités $D_f(h)$

à partir des deux formules

$$\xi_f(p) = \lim_{s \to 0} \frac{\log \int_{\mathcal{T}} \left[\Delta T_f(s,t)\right]^p dt}{\log s}, \quad \forall p \in \mathcal{P} \subset \mathbb{R}. \tag{9}$$

et

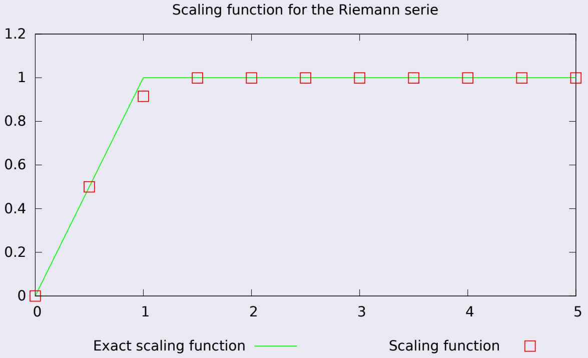
$$D_f(h) = \min_{q \in \mathbb{R}} \left\{ qh - \xi_f(q) + m \right\}. \tag{10}$$

L'algorithme

- Compute $\Delta T_f(s,t)$ with Minplus for scales $s \in \mathcal{S} \subset \mathbb{R}^{+*}$ and for $t \in \mathcal{T} \subset \mathbb{R}^m$.
- Perform linear regression at small scales s ($s \to 0^+$) with mean of relation (9) and classical integration methods in order to obtain $\xi_{f,(\min,+)}(p)$.
- Minimisation of equation (10) in order to get singularities spectrum $D_{f,(\min,+)}$.

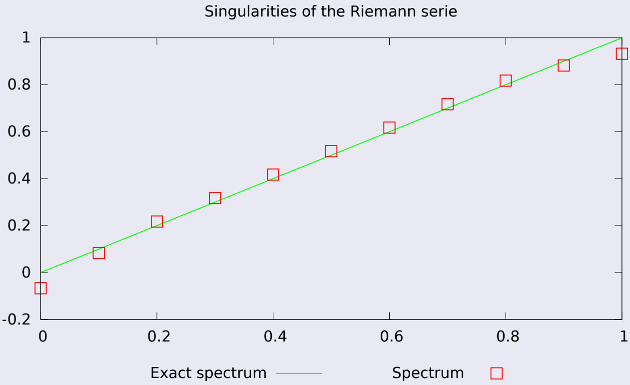
Representation of the Riemann serie $R(x) = \sum_{m=1}^{\infty} \frac{nx - [nx]}{n^2}$ with 2^{10} points.

$D(h) = h$ for $h \in [0, 1]$, and scaling function is
$\xi_R(p) = p \cdot \mathbb{I}_{[0,1]}(p) + \mathbb{I}_{[1,+\infty]}(p)$ for $p \geq 0$.

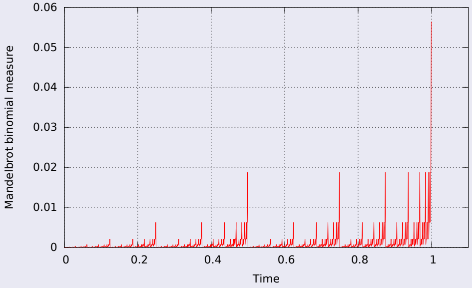


Exact and numerical scaling functions of the Riemann serie $R(x) = \sum_{m=1}^{\infty} \frac{nx-[nx]}{n^2}$ with $\hat{h}_\infty$ analysing function. Relative error in l^2-norm is about $\simeq 2.50\%$.

Analyse multifractale : série de Riemann



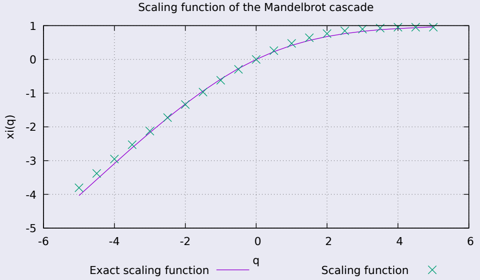
Exact and numerical singularities spectra of the Riemann serie $R(x) = \sum_{m=1}^{\infty} \frac{nx-[nx]}{n^2}$ with $\hat{h}_\infty$ analysing function. Relative error in l^2-norm is about $\simeq 4.92\%$.



Mandelbrot cascade in one dimension for probability $p = 0.25$ and 10 levels.

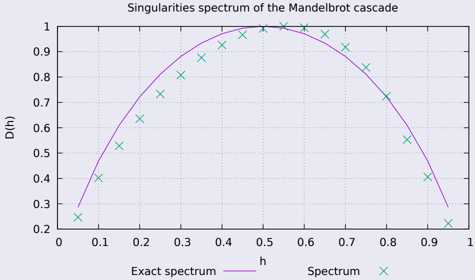
$$D(h) = -\{h \log_2 h + (1-h)\log_2(1-h)\}, \ \forall h \in]0,1[$$

fonction d'échelle



Mandelbrot cascade exact and numerical scaling function for probability $p = 0.25$ and 10 levels with $\hat{h}_\infty$ analysing function. Relative error in l^2-norm is about $\simeq 2.50\%$.

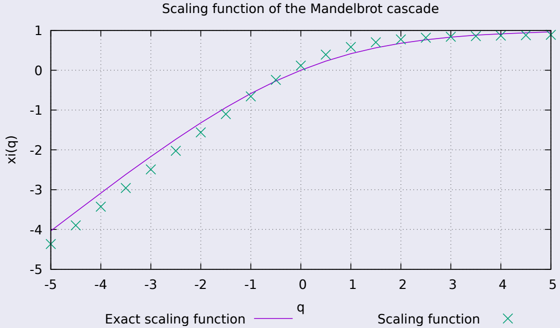
spectre de singularité



Mandelbrot cascade exact and numerical spectra for probability $p = 0.25$ and 10 levels with $\hat{h}_\infty$ analysing function. Relative error in l^2-norm is about $\simeq 5.62\%$.

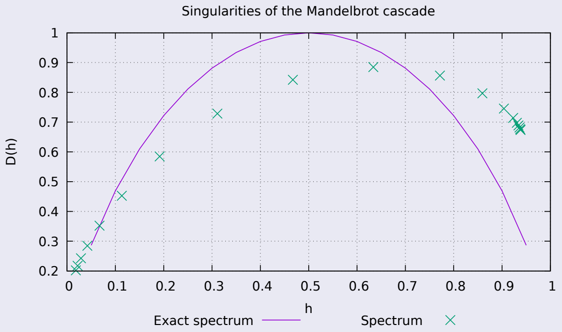
$$D(h) = -\{h \log_2 h + (1-h)\log_2(1-h)\},\ \forall h \in]0,1[$$

comparaison avec MMTO : fonction d'échelle



Mandelbrot cascade exact and numerical scaling function for probability $p = 0.25$ and 10 levels computed with WTMM method using continuous gaussian wavelet of level 7 as analysing function. Relative error in l^2-norm is about $\simeq 11.65\%$.

comparaison avec MMTO : spectre de singularité



Mandelbrot cascade exact and numerical spectra for probability $p = 0.25$ and 10 levels computed with WTMM method using continuous gaussian wavelet of level 7 as analysing function. Relative error in l^2-norm is about $\simeq 37.68\%$.

Conclusion

outil prometteur qui semble bien adapté

- simplicité
- temps de calcul
- prise en compte de fonctions très générales

outil validé théoriquement

à appliquer à d'autres domaines

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One contribution of 13 to a theme issue 'The major synthetic evolutionary transitions'.

Subject Areas:
computational biology, evolution

Keywords:
language evolution, grammaticalization, emergence of grammar, fluid construction grammar, agent-based models, major transitions in evolution

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Agent-based models for the emergence and evolution of grammar

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Human languages are extraordinarily complex adaptive systems. They feature intricate hierarchical sound structures, are able to express elaborate meanings and use sophisticated syntactic and semantic structures to relate sound to meaning. What are the cognitive mechanisms that speakers and listeners need to create and sustain such a remarkable system? What is the collective evolutionary dynamics that allows a language to self-organize, become more complex and adapt to changing challenges in expressive power? This paper focuses on grammar. It presents a basic cycle observed in the historical language record, whereby meanings move from lexical to syntactic and then to a morphological mode of expression before returning to a lexical mode, and discusses how we can discover and validate mechanisms that can cause these shifts using agent-based models.

This article is part of the themed issue 'The major synthetic evolutionary transitions'.

1. Stages in language evolution

A human language is a remarkable, highly complex communication system. The capacity for language, the so-called language-ready brain [1], uniquely emerged in the hominin species, perhaps being in place as far back as half a million years ago [2]. Since then, languages have been born, and existing languages have kept changing, diversifying and dying. How can we develop a scientific understanding of the emergence and continuous cultural evolution of such a highly complex system? Analogous to a successful strategy in evolutionary biology [3], we could postulate different stages for the emergence of language in a population with language-ready brains, based on criteria related to the complexity of the meanings that can be conveyed and the complexity of the structures and linguistic forms available to express them.

To study how complexity at each stage arises and what is required to see transitions between stages, we could adopt the synthetic method, which is being used increasingly in many scientific fields, particularly biology [4], but also fields studying culturally evolving systems, such as sociology [5] or archaeology [6]. This method suggests that we should build operational models that generate analogous behaviours to those observed in the natural system we want to understand, similar to the way an aeroplane can be said to exhibit a similar capacity to fly as birds and hence informs us about what it takes to fly. In the case of language, the operational models take the form of a population of artificial agents which are initialized with a set of cognitive mechanisms and interaction patterns—but no language system—and after a significant series of interactions, usually called language games, we expect to see a communication system emerge that has similar properties as found in human languages, such as recursive syntax or rich conceptual structure [7–9]. The synthetic methodology is not only being applied using computer simulations [10], but also using physical robots (see figure 1 from [11]), so that the behaviour of the agents is embedded in reality and issues related to the perceptual grounding of language, and the relation of language to physical action can be addressed. In such cases, agent-based models resemble the artificial systems considered in synthetic biology [12], because they are embedded in the 'real' physical world.

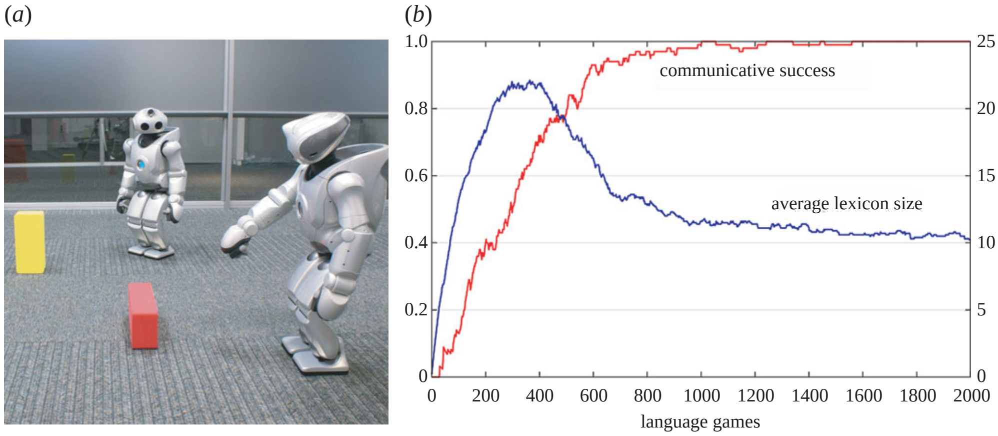

Figure 1. Example of an agent-based study for the origins of words. (*a*) Physical robotic agents are put in an open-ended environment with various geometric objects. To draw attention to an object, one robot identifies and then names the object, and the other robot then points to it. This language game is a success if the object pointed to by the listener is the one intended by the speaker. (*b*) A population of 10 agents starts without a vocabulary or any knowledge of the characteristics of each individual object. Speakers invent words for unexpressed meanings, listeners adopt the words they have not heard, and both align their lexicons based on success and failure in the game. The *x*-axis plots a series of 2000 games naming a set of 10 objects in different positions and seen from different angles. The *y*-axis shows both the average size of the lexicon (right *y*-axis, blue line), which shows a burst to 20 words and then a decrease to an optimal vocabulary of 10, and communicative success (left *y*-axis, red line), which rises to more than 95% after a mere 800 games. (Online version in colour.)

The main advantages of the synthetic methodology are that (i) all internal states of the operational model can be tracked, for example, in contrast to humans, we can monitor the complete brain states of a robot as it is learning and processing language; (ii) experimental conditions can be varied in a controlled way, so that we can isolate the causal effect of a particular factor, e.g. increased population size, a new concept formation mechanism, increased communicative pressure; and (iii) a space of possible evolutionary linguistic pathways can be explored that have not necessarily occurred in nature, giving a theoretical tool for studying the space of possible languages.

This paper illustrates this methodology, focusing on the emergence of grammar. It is the final one of the three stages commonly recognized in language evolution research.

(i) *From action to gesture*. The first stage goes from purposeful actions, for example grasping, to symbolic communicative gestural signs, for example pointing, possibly accompanied by sounds to draw the attention of the listener. The gestures are not innate, but created and implicitly negotiated. This stage is reached by most children around the first year of life [13]. Many researchers have argued that gestural signs must have been the first stage in the origins of symbolic communication in our species as well [14], partly because closely related species, in particular chimpanzees and bonobos, also develop gestural signs among close kin [15]. Various agent-based models have tried to emulate this stage, mostly based on operationalizing ontogenetic ritualization [16–18].

(ii) *From sounds to words*. In the second stage, the sounds accompanying gestures, which were initially purely intended for grabbing the attention of the listener, become words, i.e. complex vocalizations associated with meanings [19]. This stage is reached by children in the first year of life with at first a slow acquisition rate, which then steadily increases so that around the age of 2, we typically observe a vocabulary spurt. Such a stage has also been postulated as the earliest stage in the origins of human languages [20], possibly already reached in earlier hominin species, such as *Homo heidelbergensis* [2]. Although some non-human primates can acquire a system of signs [21], these signs were always supplied by human experimenters as opposed to being self-generated, and systems do not propagate beyond close kin. Several agent-based models for stage II have been developed (see the sample in [22]). They typically take the form of language games in which agents from a population take turns being speaker and listener in order to refer to objects or actions in the shared reality, as illustrated in figure 1 discussed in Steels [11].

(iii) *From single words to grammar*. In the third stage, utterances use various syntactic devices, such as affixes, word stem changes, sequential ordering, intonation, stress patterns and hierarchical structure, in order to express additional meaning and extra information to avoid combinatorial complexity in parsing and semantic interpretation. This stage is reached in children by the end of the second year [23] and both lexicon and grammar grow rapidly until, at year five, the main grammatical systems of the language are in place, although many subtleties still need to be learned in subsequent years while the lexicon also expands further. Indeed, language learning goes on throughout life as languages are continuously changing. There is a wide consensus that humans are unique in their capacity to build up, learn and align grammatical language, even though many animal species exhibit some of the cognitive prerequisites such as recognizing and producing recursive syntax [24]. The rest of this paper discusses agent-based models for this third stage, which so far have been much less explored.

2. How grammar evolves in human languages

Historical linguists, like Wilhelm von Humboldt, already observed in the nineteenth century that the expression of meaning in a particular language is not static but cycles through different modes [25] (figure 2).

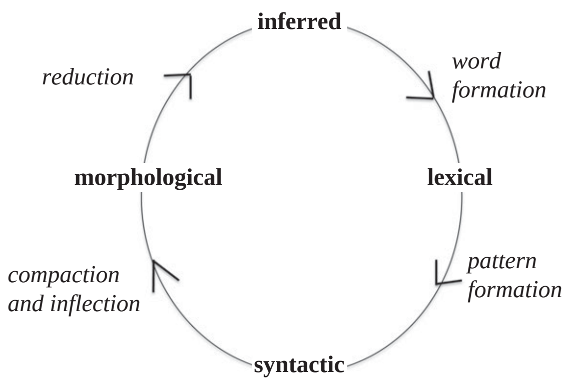

Figure 2. The expression of meaning goes through a linguistic cycle, switching between four modes: an inferential mode, in which meaning needs to be inferred; a lexical mode, where meanings are expressed with words; a syntactic mode, where they are expressed with several words organized in hierarchical structures; and a morphological mode, where phrases are compacted into single words with affixes and word form variations expressing grammatical features.

— *Mode 1. Inferred*. Human communication is inferential [26]. Speaker and listener try to come to a shared understanding of a situation, but not all meaning involved is explicitly expressed. In fact, most of it has to be inferred from the context, common sense knowledge and background information. For example, the sentence 'I want to come' does not explicitly express that the action of coming may take place in the future, but we can infer this, because the speaker expresses a desire to carry out the action, which implies that if it happens, it will be in the future.

— *Mode 2. Lexical*. A meaning fragment becomes associated with a word, and as soon as speakers and listeners master an initial inventory of word–meaning pairs, the words can be put together in multiword utterances without concern for grammar but already enabling the compositional expression of larger meanings. This mode does not require complex linguistic processing. The speaker needs to retrieve from his lexicon a set of words that together cover the overall meaning he wants to convey, and the listener needs to look up the words in his own lexicon and then infer the semantic relations between the individual meaning fragments to reconstruct the overall meaning. A lexical mode with free-floating words is the norm in the 'telegraphic speech' that characterizes the very first phases of language learning in 2 year old children beyond single words. We find it in newspaper headlines, noun complexes, queries typed into search engines, Twitter-like messages in social media, utterances by non-native speakers without knowledge of the grammar, etc.

— *Mode 3. Syntactic*. In this mode, meaning is expressed using hierarchical patterns of words. For example, the article 'the', the adjective 'Roman' and the noun 'poet' form part of the noun phrase 'the Roman poet'. The phrase as a whole can act as a unit and be combined again with other words or phrasal units, leading to hierarchical phrase structures, as in, 'the Roman poet wrote pretty boring sonnets'. A phrasal pattern often expresses meaning beyond the meanings of its constituents [27]. For example, the phrase 'ran into' in 'I *ran into* an old friend' means 'to encounter' rather than means a simple composition of the original literal meaning of 'run' (a physical movement towards a target) and 'into' (a spatial preposition meaning inside).

— *Mode 4. Morphological*. In this mode, meaning is expressed using complex word forms that have a purely lexical core 'decorated' with various markers (either clearly separable affixes or variations in the form of a word). The markers express grammatical features, such as gender, number, case, tense, aspect, definiteness, etc., and form an inflectional system. An example from English is 'opened', which has 'open' as lexical core and '-ed' as an affix expressing past tense. Hierarchical structure and semantic relations between words are now expressed through grammatical agreement instead of word ordering. Grammatical agreement means that certain grammatical features, such as gender or number, are shared between words that are semantically related. Because the structure is expressed through feature marking, words or phrases can be free-floating again, like in a lexical mode.

When looking at a particular language, we find that all four modes are used, although usually one of them is dominant. For example, English is predominantly an *analytic* language, i.e. primarily relying on syntax (mode 3), even though there are some meaning domains using a morphological approach, for example, past tense expression in irregular verbs (came/come, do/did) or expression of semantic roles (cases) in pronouns (he/him/his). Quechuan, a native American language, is predominantly a *synthetic* language, i.e. primarily relying on morphology (mode 4). Nouns have no less than 19 possible case suffixes, and seven possessive suffixes. Verbs have a variety of suffixes to indicate tense, aspect, mood and modality, and various markers to convey subtle aspects of meaning. For example, an action verb may have additional markers to express the nature of the action, how the action was executed, which type of instrument was used, which evidence was available, etc. [28]. All this information is expressed in English, using separate words organized in syntactic patterns.

The historical record shows that the language inventory tends to expand for each mode. We see growth in the lexicon, increase in morphological complexity [29], increase in the sophistication of syntactic patterns [30]. However, we also see weakening and erosion within a given mode that may lead to a shift between modes, a process that is commonly called grammaticalization [31–33].

A typical example comes from the domain of time, such as the expression of future [34]. We see languages where future is not expressed explicitly or very ambiguously, and it therefore has to be inferred (as is currently the case in Chinese). Then, a stage may develop where future is expressed syntactically with a verb phrase and an auxiliary (as in English 'I will come'). Typically, a verb such as 'want' or 'go to', which indirectly suggests future, is recruited and then becomes grammaticalized to take on the role of a future auxiliary. Next, we may see the compaction of a phrasal pattern into a single word, as in French 'Je partirai' (I will leave), which comes from an earlier syntactic expression of future with the verb 'habere' (have) as in 'partire habeo' (literally, 'to leave I have'). The words in this pattern were increasingly glued together and compacted to 'parti-abeo', then 'partir-ayo', which finally ended up through further phonetic optimization as 'partirai' (French first person singular future of 'partire') [35].

Although mode shifts typically take place over long time periods (thousands of years), there can be sudden accelerations, often owing to catastrophic events causing punctuated equilibria [36]. For example, in the formation of creole languages, the grammatical structures of the source language (e.g. French) get stripped away almost entirely to yield a lexical language (mode 2 dominating) from which the grammaticalization processes start off again and quite rapidly (in one or two generations) lead to a novel fully functioning grammatical system [37].

Language evolution usually moves in the direction from lexical to syntactic and then morphological, but there are occasionally movements in the other direction [38]. For example, the form of a word may erode so strongly that the meaning is no longer clearly expressed at which point a re-invention takes place. For example, the Latin word for speaking 'loqui' went out of use in late colloquial Latin to be replaced by 'fabulare', which evolved into Spanish 'hablar', or 'parabolare', which evolved into French 'parler' [35]. The negation particle 'ne' in French, itself already a reduction from 'non', was felt as too weak and was reinforced syntactically with the particle 'pas' (literally step) as in 'je ne veux pas' (I do not want). Today, 'ne' has become optional and 'pas' has effectively become the negation particle, as in 'je veux pas' (colloquial contemporary French).

These uncontested facts suggest that we should not conceptualize the origins and evolution of language as an all-or-none phenomenon, perhaps owing to a single genetic mutation that gave rise to a single new operator (such as merge). Instead, it makes more sense to inquire about the many cognitive mechanisms, the invention, learning and alignment strategies, and the cultural evolutionary dynamics that have to be in place so that a population of individuals can sustain these linguistic cycles in the expression of meaning domains. The mechanisms include analogical inference, routinization of behaviour, optimization, analogical inference, hierarchical planning and plan recognition, concept formation, imitation, associative memory and no doubt many more. Whether these cognitive mechanisms are specific to a language, and therefore would have required neurobiological change, or not can only be discussed seriously if we have adequate operational models of what these mechanisms are.

3. Agent-based models of language evolution

Agent-based models are a good way to tease apart and investigate the many mechanisms and factors involved in explaining linguistic cycling, because we can explicate a certain factor or mechanism (e.g. a particular concept formation strategy or a particular mechanism for analogical inference) and study its effect on the emergence or change how a particular meaning domain (e.g. colour, space or time) gets expressed. Moreover, there are not only cognitive factors, but also external factors influencing the evolutionary dynamics; for example, strong language contact may lead to intensive borrowing and the subsequent collapse of phrasal or morphological patterns, significant population turnover may compromise cultural transmission, differences in frequency for meanings and forms may accelerate shifts to another mode or reorganization of the grammar [39]. All these factors can be incorporated in an agent-based model and their impact studied by systematically changing them, for example, by allowing slower or faster population turnover.

Much remains to be done, as this methodology is only now beginning to be applied on a sufficiently large scale, but there is already a body of significant case studies. Most importantly, research is converging on a core set of mechanisms and processes, so that the hugely complicated effort to set up an agent-based model becomes more doable. Our group has made concrete proposals for such a core and translated them into a computational workbench for doing evolutionary linguistics experiments that is freely downloadable from https://www.fcg-net.org/.

The common core in all our experiments includes the following components:

(i) *A script-based interaction engine*. It governs the turn-taking interaction between speakers and listeners.

(ii) *A semantic representation formalism*. Agents in all modes use the same system for representing and manipulating meaning, based on a variant of second-order intentional logic. The representation includes objects in the domain of discourse denoted as symbols, e.g. o2, o3, etc., and n-ary predicates for the properties, relations or actions involving these objects, e.g. *red(o2)*, *next-to(o1,o2)*, etc. The semantic representations are second order, because a property or relation can itself be an object and the intension (the predicate itself) can also be an object. The details of this representation formalism are not important for the main points of this paper.

(iii) *Representation of situation models*. Situation models are couched in terms of this semantic representation formalism. A situation model contains all the objects and relations known about the shared context. It is private to each agent and not necessarily shared. In robotic experiments, the situation model is obtained from sensors and complex sensory processes that anchor objects in experienced reality and compute which predicates are true in the current context [40]. For example, a scene with a red ball that is inside a green box (which might occur in the experiments shown in figure 1) is represented with the following set of predications:

$$red(o1),\quad green(o2),\quad ball(o1),\quad block(o2)\ \text{and}\ inside(o1,o2). \tag{3.1}$$

(iv) *Representation of utterance meaning*. The meaning of utterances is obtained by the listener through parsing an utterance, and by the speaker through conceptualizing 'what to say' in order to achieve a particular communicative goal. The utterance meaning uses the same semantic representation formalism as situation models. However, expressions now have variables instead of constants. These variables are written as symbols with a question mark in front, such as ?*x1*, ?*x2*, etc. Semantic interpretation consists of matching utterance meaning against the situation model in order to find bindings for all the variables. For example, the utterance 'ball red next-to block' (assuming no grammar) gets translated by a lexical parsing process that looks up the word meanings and combines them into a set

$$ball(?x1),\quad red(?x2),\quad box(?x3)\ \text{and}\ inside(?x4,?x5). \tag{3.2}$$

A possible binding for these variables, given the situation model in (3.1) is

$$?x1 = o1, \quad ?x2 = o1, \quad ?x3 = o2, \quad ?x4 = o1 \quad \text{and} \quad ?x5 = o2.$$

Grammar primarily signals some of the co-reference relations between variables. For example, if we take the English utterance '(the) red ball inside (the) box', then the listener knows, even before consulting the situation model, that $?x1 = ?x2$, because the words 'red' and 'ball', which introduce the predicates 'red' and 'ball', are part of the same noun phrase. Moreover, he knows from the semantics of the preopositional noun phrase construction that

$$?x4 = ?x1 = ?x2 \quad \text{and} \quad ?x3 = ?x5.$$

(v) *A construction grammar engine*. Construction schemas are relevant for all modes, whether they capture lexical, morphological or syntactic ways of expressing meaning. A construction schema defines an association between meaning and form, for example the predicate 'red($?x$)' and the word 'red'. Or article, adjective and noun units are combined in a noun phrase that also establishes semantic relations between the meaning of these units. A construction schema has slots for the different units (words or phrases), and specifies the syntactic and semantic constraints on the units and their morphosyntactic properties. It specifies how to build a new unit for the parent, and associates grammatical and semantic categories with that unit. In contrast to purely syntactic formalisms (such as minimalism), construction schemas always contribute meaning beyond the meaning of their constituents, such as co-reference relations between the meanings of constituents or additional predicates. Construction grammar typically organizes schemas into networks to support priming and inheritance from more abstract to more concrete constructions.

We have developed an operational version of construction grammar, called fluid construction grammar (FCG) [41]. Details of FCG are complex, but not crucial for the present discussion. The most important point is that FCG uses the same schema representation and the same processing mechanisms for lexical, syntactic and morphological constructions, so that agents can smoothly move between the three different modes of meaning expression described earlier. Another important characteristic of FCG is that the same construction schema can be used in parsing as well as production, so that the speaker can monitor his own speech by simulating how the listener might interpret the utterance he is producing, and the listener can simulate how he would express the meaning he was able to derive from the speaker's utterance.

(vi) *Learning architecture*. Finally, all agents are equipped with a general architecture that supports insight learning [42,43]. There are two layers of processing: a routine layer where agents apply the constructions available at that point in their individual inventory, and a metalayer where agents apply diagnostics and repair strategies. A *diagnostic strategy* triggers when routine application of constructions is not possible, when the outcome after applying available constructions is incomplete or not interpretable with the current situation model, or when an opportunity for possible optimization is detected. A *repair strategy* attempts to deal with issues diagnosed by these diagnostics. For example, if a word is missing for expressing a fragment of utterance meaning, then the speaker may invent or recruit a new word; if a phrase or part of a phrase is recurring often, it may be compacted in a single word by changing the intonation structure and pauses between words; if a co-referential relation between two variables is not expressed, a grammatical construction might be introduced to convey this information to avoid semantic ambiguity in the future, etc. After an interaction, *consolidation strategies* come into action. They translate repairs into new constructions or variations on existing constructions, perform credit assignment and restructure the grammar.

(vii) *Cultural evolutionary dynamics*. All models we developed are based on an instantiation of evolutionary dynamics at the cultural, more precisely linguistic, level. Evolutionary dynamics requires that there is a population of units that multiply with inheritance, exhibit variation and undergo selection, effecting the distribution of traits. Here, the traits are strategies and constructions built with them, stored in the individual memories of the agents. They multiply through social learning as a part of language games. Variation is unavoidable owing to performance deviations, creative language use and imperfect learning. Selection takes place, because the agents prefer constructions that lead to higher communicative success, adequate expressive power and minimized cognitive effort, causing some strategies and constructions to propagate and become dominant in the language community. Language evolution never stops, because there is no optimal solution and no central authority, so that the population keeps navigating in the space of possible language variants to have a communication system adapted to their needs.

4. Case studies

From §3, it follows that setting up a specific agent-based model requires: a definition of a game script, an environment that will be the source of meanings, a population with possibly internal structure and dynamics and most importantly operational diagnostic, repair and consolidation strategies, so that we can see what their effect is on the emerging language. An experiment will typically focus on one aspect of language. These can be quite specific, for example, how can an inventory of colour terms and colour categories arise, how can a system expressing tense and aspect emerge, how does phonetic erosion lead to the collapse of a case system. It can also be more general, for example, how can a recursive phrase structure grammar emerge, what is the impact of analogy on streamlining an inflection system, what is the impact of population structure and renewal on the emergence and preservation of a lexicon. The remainder of this paper can only give a few concrete examples with details contained in the cited papers.

(a) Word formation

Agent-based models for word formation have to explain how implicit, inferred meanings can turn into explicit lexical expression. This happens in the experiment shown in figure 1 in which agents play naming games about visually

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Table 1. Word formation strategy.

role	diagnostic	repair	consolidation
speaker	word is missing for a meaning fragment	invent new word form	build new construction associating meaning with newly invented word
listener	unknown word	guess possible meaning	new construction associating guessed meaning with unknown word

Table 2. Phrase building strategy.

role	diagnostic	repair	consolidation
speaker	disconnected unit (co-referential relations not expressed)	build variant of best matching construction by adding the unit	store this constructional variant
listener	disconnected unit (unexpressed co-referential relations)	relations deduced through speaker feedback and situation model	build constructional variant adding unit to best matching construction

Table 3. Coercion.

role	diagnostic	repair	consolidation
speaker	disconnected unit (co-referential relations not expressed)	find best matching construction and coerce unit so that it fits	store the expanded combination potential of the coerced unit
listener	disconnected unit (co-referential relations not expressed)	infer additional co-referential relations from situation model	store the expanded combination potential of the coerced unit

Table 4. Phonetic reduction.

role	diagnostic	repair	consolidation
speaker	is optimization possible?	leave out final consonant or vowel	store the new form as a constructional variant
listener	form matches only partially with existing one	use best matching construction	store new word form as a construction variant

perceived objects in a shared situation using the diagnostic, repair and consolidation strategy shown in table 1.

Consolidation also needs to include credit assignment using the following strategy:

(i) In the case of a *successful* interaction, all new or modified constructions are stored and the scores of the constructions that were involved are increased, whereas competing constructions, i.e. constructions that could also potentially apply but lead to a dead end or to some other anomaly, are decreased, thus implementing the kind of lateral inhibition dynamics familiar from many neural network models, such as the Kohonen network.

(ii) In the case of a *failed* interaction, the scores of the implicated constructions are decreased, and new or modified constructions are not stored.

We see in figure 1 that these strategies indeed allow a population of agents to expand and share a lexicon. Words propagate but there is variation, because different agents may invent a new word when they do not have one. Progressively, some words win the competition based on the lateral inhibition dynamics and a shared lexicon with a minimal set of words for the meaning domain results. These strategies have already been applied for a variety of meaning domains, including experiments where both the categories and the lexicon evolve and get coordinated [44]. Experiments have also been conducted on word formation with multiword utterances (without grammar) using slightly more sophisticated diagnostic, repair and consolidation strategies [45].

(b) Syntax formation

Agent-based models for syntax formation have to explain how a set of words can get organized into hierarchical phrasal patterns. This happens in the experiment shown in figure 3 (from [43]) where agents play the syntax game [46], which is a variant of the naming game that requires the expression of n-ary relations, such as 'inside-of' or 'moves-towards', and hence ambiguity about the role of the arguments in the relation. Figure 3 is based on two strategies: one for building phrasal patterns by incorporating units, and another one for fitting existing words or phrases into an existing phrasal pattern through coercion [43].

The phrase-building strategy creates an extended phrasal pattern, which initially contains just a single word, by incorporating an additional constituent. For example, the pattern 'blue block' is extended, so that an extra property is expressed, as in 'big blue block'. The new variant inherits most of its properties from the partially applicable construction (table 2).

The coercion strategy extends the lexical or phrasal categories of a unit, so that it fits a schema. For example, in the phrase 'she WhatsApped me', the noun 'WhatsApp' is coerced to behave as a verb, so that the clausal construction combining subject, verb and object, can apply (table 3).

Figure 3 shows the effect of these strategies when a population of five agents plays 800 syntax games. The experimental results show not only that agents converge on a shared phrase structure grammar (seen because alignment reaches almost 100%), but also that semantic and syntactic ambiguity decreases significantly to close to zero, implying that a 'better' communication system arises, meaning one with less cognitive effort and less risk for misunderstanding. Different agents may select different word orders to express the same co-reference relations, and so there is unavoidably competition. Agents may also differ on the grammatical categories of words. However, the lateral inhibition credit assignment strategy, the same as used for word formation, causes convergence of word ordering and categorical usage.

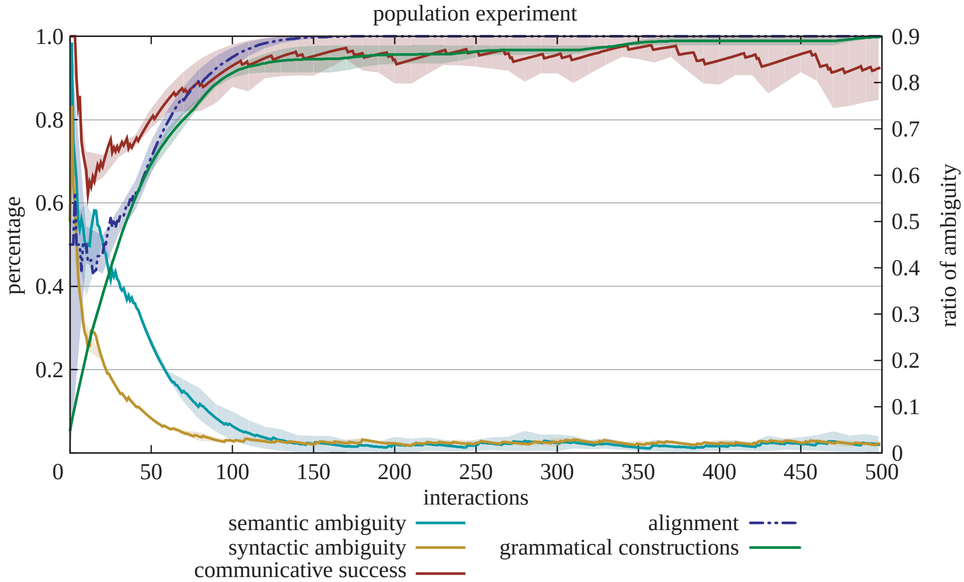

Figure 3. Grammar emergence experiment shows 500 consecutive language games in a population of five agents. The running average of four different measures is shown: (i) *semantic ambiguity* measures the number of times the situation model had to be used to generate or block hypotheses, divided by the number of variables in the utterance meaning; (ii) *syntactic ambiguity* measures the percentage of failed paths in the search space; (iii) *communicative success* measures whether the hearer was able to identify the topic without speaker feedback; (iv) *alignment* measures whether the hearer would express the same meaning using the same utterance as the speaker; and (v) *grammatical constructions* measures the learning rate, i.e. how fast the grammar is acquired, by tracking the percentage of constructions of the final grammar already learned at each time step. (Online version in colour.)

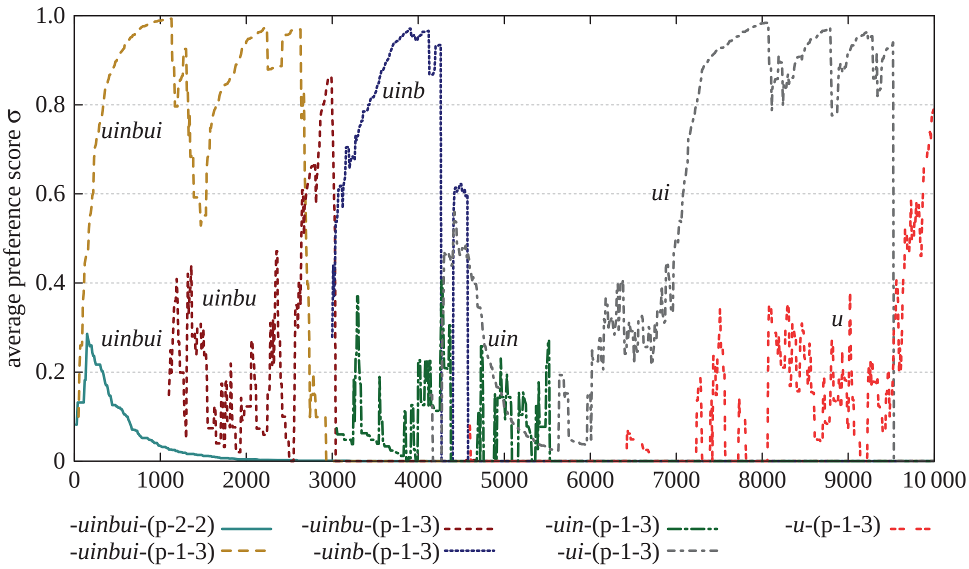

Figure 4. Changes to an agreement marker during a single experiment in a population of 10 agents which are using the phonetic reduction strategy. The probability that the speaker reduces a marker is $e = 0.1$ per game. The marker *-uinbui* erodes progressively to *-u*. A truncated variant is typically present for a while in the population until it becomes dominant. If the *-u* marker is cut further, its function gets lost and must be regenerated. (Online version in colour.)

(c) Reduction

Agent-based models for the phonetic erosion of meaning have to explain how words or morphological markers of words can progressively simplify without compromising initially their use, until of course the form has completely disappeared. This is illustrated in the experiment shown in figure 4 taken from larger-scale experiments in the emergence of marker systems and agreement [47]. Simplifying, the speaker attempts to diminish the articulatory complexity of a form (with a certain probability) and the listener accepts this form-variant if it is close enough to an existing form and if its acceptance leads to a successful game, after which the listener consolidates the form-variant in a new construction as part of his own inventory. Results in figure 4 show this strategy at work with new variants popping up, and spreading in the population, without compromising communicative success, until they become dominant, after which a new variant comes up (table 4).

5. Conclusion

Agent-based modelling can play an important role in deconstructing the many factors that play a role in the emergence and evolution of language. It helps to tease these factors apart and study their causal impact on an evolving language in repeatable objective experiments. Data from historical linguistics have abundantly demonstrated that there are different modes in which a particular meaning domain can get expressed (inferred, lexical, syntactic and morphological) and that we regularly see mode shifts creating linguistic cycles. For example, temporal information, such as future, may go from being unexpressed, to being expressed using words, auxiliaries in verbal patterns, and compact morphological expression in an inflectional system. A theory of language evolution needs to show by what cognitive mechanisms, external factors and evolutionary dynamics meanings get expressed in each of these modes and how shifts may occur.

This paper puts forward a common core with a script-based interaction engine, semantic representations for situation models and utterance meaning, an operational model of construction grammar processing, and a meta-level learning architecture enabling insight learning. It also puts forward a model of the cultural evolutionary dynamics and then points to a number of case studies that are using this core for achieving word formation, syntax formation and phonetic reduction. Clearly, language is an extraordinarily complex adaptive system. We therefore should not expect a single simple explanation how such a system can emerge and keep evolving, and many more experiments are needed on all aspects of the linguistic cycle.

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