Computational Biology II

What is computational biology?

Discipline that uses mathematical/computational techniques to address questions in biology.

Computational biology in practice

Science 9 June 2000:
Vol. 288 no. 5472 pp. 1789–1796
DOI: 10.1126/science.288.5472.1789

RESEARCH ARTICLE

Timing the Ancestor of the HIV-1 Pandemic Strains

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ABSTRACT

HIV-1 sequences were analyzed to estimate the timing of the ancestral sequence of the main group of HIV-1, the strains responsible for the AIDS pandemic. Using parallel supercomputers and assuming a constant rate of evolution, we applied maximum-likelihood phylogenetic methods to unprecedented amounts of data for this calculation. We validated our approach by correctly estimating the timing of two historically documented points. Using a comprehensive full-length envelope sequence alignment, we estimated the date of the last common ancestor of the main group of HIV-1 to be 1931 (1915–41). Analysis of a gag gene alignment, subregions of envelope including additional sequences, and a method that relaxed the assumption of a strict molecular clock also supported these results.

Computational biology in practice

HIV-1 Dynamics in Vivo: Virion Clearance Rate, Infected Cell Life-Span, and Viral Generation Time

Alan S. Perelson, Avidan U. Neumann, Martin Markowitz, John M. Leonard, David D. Ho*

A new mathematical model was used to analyze a detailed set of human immunodeficiency virus–type 1 (HIV-1) viral load data collected from five infected individuals after the administration of a potent inhibitor of HIV-1 protease. Productively infected cells were estimated to have, on average, a life-span of 2.2 days (half-life $t_{1/2} = 1.6$ days), and plasma virions were estimated to have a mean life-span of 0.3 days ($t_{1/2} = 0.24$ days). The estimated average total HIV-1 production was 10.3×10^9 virions per day, which is substantially greater than previous minimum estimates. The results also suggest that the minimum duration of the HIV-1 life cycle in vivo is 1.2 days on average, and that the average HIV-1 generation time—defined as the time from release of a virion until it infects another cell and causes the release of a new generation of viral particles—is 2.6 days. These findings on viral dynamics provide not only a kinetic picture of HIV-1 pathogenesis, but also theoretical principles to guide the development of treatment strategies.

Computational Biology II

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Computational biology vs bioinformatics?

Loosely speaking, the emphasis in bioinformatics is on the life cycle of the data (organization, storage and retrieval, visualization), and in computational biology on biological questions, which are addressed by combining (large-scale) data analysis with mathematical modeling and simulation.

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2011 PLoS COMPUTATIONAL BIOLOGY

Perspective

The Roots of Bioinformatics in Theoretical Biology

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Abstract: From the late 1980s onward, the term "bioinformatics" mostly has been used to refer to computational methods for comparative analysis of genome data. However, the term was originally more widely defined as the study of informatic processes in biotic systems. In this essay, I will trace this early history (from a personal point of view) and I will argue that the original meaning of the term is re-emerging.

Computational Biology II

Why computational biology?

• Biology is changing from a descriptive to a quantitative science.

• We now know most of the components of cells and organisms; recent techniques allow us to get *high-throughput*, *quantitative measurements* of these components in different conditions.

• How do we make sense of what is going on?

• How do we infer principles of functional organization?

But…

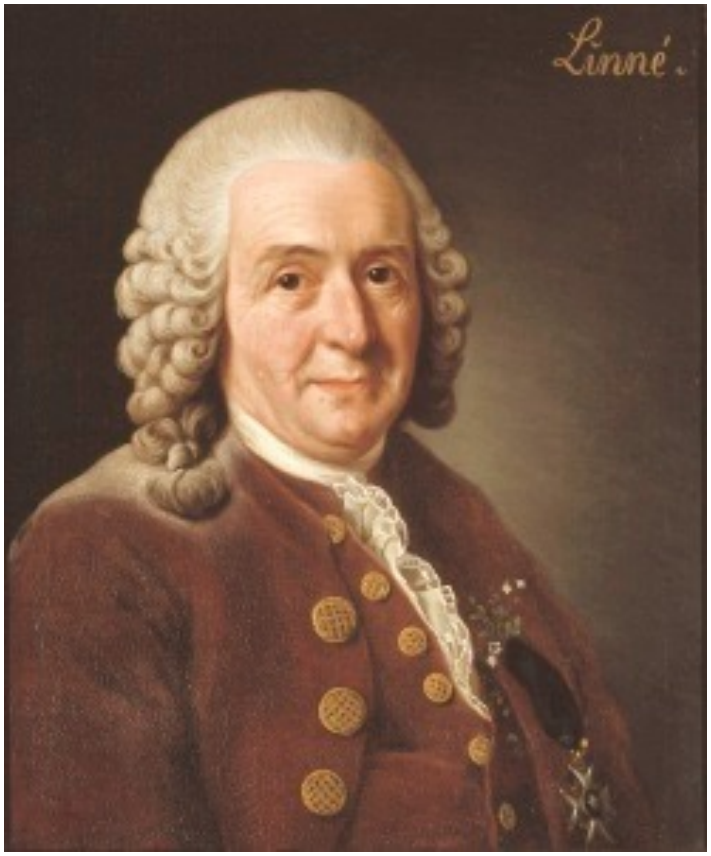
Are there organizational principles in biology?

What do they look like?

Linnaean taxonomy

Systema Naturae, 1735

Carl Linnaeus (1707-1778)
Swedish natural scientist



- Organized “nature”
  - living and non-living things
- Standardized the naming of species

Kingdom (Animal, Vegetal, Mineral)
Class
Genus
Species

- System describing organisms currently in existence
- Based on morphologic similarity

CAROLI LINNÆI REGNUM ANIMALE.

I. QUADRUPEDIA.

Corpus hirsutum. *Pedes* quatuor. *Feminæ* viviparæ, lactiferæ.

Ordines.	Genera.	Characteres Generum.	Species.
ANTHROPOMORPHA. *Dentes* primores 4. utrinque: vel nulli.	Homo.	Nosce te ipsum.	H { Europæus albesc. Americanus rubesc. Asiaticus fuscus. Africanus nigr.
	Simia.	ANTERIORES. POSTERIORES. *Digiti* 5. . . . . . 5. Posteriores anterioribus similes.	Simia cauda carens. Papio. Satyrus. Cercopithecus. Cynocephalus.
	Bradypus.	*Digiti* 3. vel 2. . . 3.	Ai. *Ignavus.* Tardigradus.
FERÆ. *Dentes primores* 6. utrinque: *intermedii* longiores: *omnes* acuti. *Pedes* multifidi, unguiculati.	Ursus.	*Digiti* 5. . . . . . 5. Scandens. *Mammæ* 4. (Ald.) *Calcaneis* insistit. *Pollex* extus positus.	Ursus. Coati *Mrg.* Wickhead *Angl.*
	Leo.	*Digiti* 5. . . . . . 4. Scandens. *Mammæ* 2. ventrales. *Lingua* aculeata.	Leo.
	Tigris.	*Digiti* 5. . . . . . 4. Scandens. *Mammæ* 4 umbilicales. *Lingua* aculeata.	Tigris. Panthera.
	Felis.	*Digiti* 5. . . . . . 4. Scandens. *Mammæ* 8. sc. 4. pect. 4. abdom. *Lingua* aculeata.	Felis. Catus. Lynx.
	Mustela.	*Digiti* 5. . . . . . 5. Scandens. *Dentes* molares 4. utrinque.	Martes. Zibellina. Viverra. Mustela. Putorius.
	Didelphis.	*Digiti* 5. . . . . . 5. *Mammæ* 8. intra bursulam abdomin.	Philander. *Possum.*
	Lutra.	*Digiti* 5. . . . . . 5. Palmipes.	Lutra.
	Odobænus.	*Digiti* 5. . . . . . 5. Palmipes. *Dentes* intermedii superiores longiss.	Ross. *Morsus.*
	Phoca.	*Digiti* 5. . . . . . 5. Palmipes. *Mammæ* duæ umbilicales.	Canis marinus.
	Hyæna.	*Digiti* 4. . . . . . 4. *Collum* superne jubatum. *Cauda* brevis.	Hyæna *Veter.* *Vivam Londini nuper vidit & descripsit* ARTED.
	Canis.	*Digiti* 5. . . . . . 4. *Mammæ* 10. sc. 4. pect. 6. abdom.	Canis. Lupus. Squillachi. Vulpes.
	Meles.	*Digiti* 5. . . . . . 5. *Ungues* medii digitis ipsis longiores. *Corpus* superne albicat: inferne nigricat.	Taxus. Zibetha.
	Talpa.	*Digiti* 5. . . . . . 5. *anteriores* maximi.	Talpa.
	Erinaceus.	*Digiti* 5. . . . . . 5. *Spinis* vel *lorica* squamosa munitus.	Echinus terrestris. Armadillo.
	Vespertilio.	*Digiti* 5. . . . . . 5. *Pes anticus* in alam expansus. *Mammæ* 2. pectorales.	Vespertilio. Felis volans *Seb.* Canis volans *Seb.* Glis volans *Seb.*
GLIRES. *Dentes primores* 2. utrinque. *Pedes* multifidi.	Hystrix.	*Aures* humanæ. *Corpus* spinosum.	Hystrix.
	Sciurus.	*Digiti* 4. . . . . . 5. *Cauda* longissima lanigera.	Sciurus. . . . volans.
	Castor.	*Digiti* 5. . . . . . 5. palmipes postice. *Cauda* horizontalis, plana, nuda.	Fiber.
	Mus.	*Digiti* 4. . . . . . 5. *Cauda* teres, squamosa, hirsuta.	Rattus Mus domesticus. . . brachiurus. . . macrourus. Lemures. Marmota.
	Lepus.	*Digiti* 5. . . . . . 4. *Cauda* brevissima, villosa.	Lepus. Cuniculus.
	Sorex.	*Digiti* 5. . . . . . 5. *Dentes canini* adsunt.	Sorex.
JUMENTA. *Dentes primores* incerti, obtusi. *canini* exerti, validi.	Equus.	*Mammæ* 2. inguinales. *Pedes* integri.	Equus. Asinus. Onager. Zebra.
	Hippopotamus.	*Mammæ* 2. inguinales (*Arist.*) *Pedes* quadrifidi.	Equus marinus.
	Elephas.	*Mammæ* 2. pectorales. *Pedes* 5. callis instructi.	Elephas. ? Rhinoceros.
	Sus.	*Mammæ* 10. abdominales. *Pedes* bisungulati: raro simplices.	Sus. Aper. Porcus. Barbyroussa. Tajacu.
PECORA. *Dentes primores* inferiores tantum: *Superiores* nulli. *Pedes* ungulati.	Camelus.	*Cornua* nulla.	Dromedarius. Bactrianus. Glama. Pacos.
	Cervus.	*Cornua* annua, primum pilosa, solida, ab apice crescentia, plurimis ramosa: feminis rara.	Camelopardalis. Caprea. Axis. Cervus. Platyceros. Rheno. *Rangifer.* Alces.
	Capra.	*Cornua* sursum versa, erecta, scabra.	Hircus. Ibex. Rupicapra. Strepsiceros. Gazella. Tragelaphus.
	Ovis.	*Cornua* retrorsum flexa intorta, rugosa.	Ovis vulgaris. . . Arabica. . . Africana. . . Angolensis.
	Bos.	*Cornua* antrorsum versa, lunulata, lævia.	Bos. Urus. Bison. Bubalus.
Ordines.	Genera.	Characteres Generum.	Species.

II. AVES.

Corpus plumosum. *Alæ* duæ. *Pedes* duo. *Rostrum* osseum. *Feminæ* oviparæ.

ACCIPITRES. *Rostrum* uncinatum.	Psittacus.	*Digiti* pedis antici 2. postici 2.	Psittacus.
	Strix.	*Digiti* pedis antici 3. posticus 1. quorum extimus retrorsum flexilis.	Bubo. Otus. Noctua. Ulula.
	Falco.	*Digiti* pedis antici 3. posticus 1.	Aquila. Vultur. Buteo. Falco. Cyanopus. Milvus. Lanius. Pygargus. Nisus. Tinnunculus.
PICÆ. *Rostrum* superne compressum, convexum.	Paradisæa.	*Pennæ* 2. longissimæ, singulares, nec alis, nec uropygio infixæ.	Manucodiata. Avis Paradisiaca.
	Coracias.	*Pes* 4dact. *Rectrices* exteriores gradatim breviores.	Pica.
	Corvus.	*Pes* 4dact. *Rectrices* æquales.	Corvus. Cornix. Monedula. Lupus. Glandaria. Caryocatactes.
	Cuculus.	*Digiti* pedis antici 2. postici 2. *Rostrum* læve.	Cuculus. Torquilla s. Junx.
	Picus.	*Digiti* pedis antici 2. *Rostrum* angulatum.	Picus niger. . . . viridis. . . . varius.
	Certhia.	*Pes* 4dact. *Rostr.* gracile incurvum.	Certhia.
	Sitta.	*Pes* 4dact. *Rostr.* triangulare.	Picus cinereus
	Upupa.	*Pes* 4dact. *Caput* plumis cristatum.	Upupa.
	Ispida.	*Pes* 4dact. cujus digitus extimus medio adnectitur tribus articulis.	Ispida. Merops.
MACRORHYNCHÆ. *Rostr.* longiss. acut.	Grus.	*Caput* cristatum.	Grus.
	Ciconia.	*Ungues* plani, subrotundi.	Ciconia.
	Ardea.	*Unguis* medius inferne serratus.	Ardea.
ANSERES. *Os* dentato-serratum.	Platelea.	*Rostr.* depresso-planum, *apice* subrot.	Platea.
	Pelecanus.	*Rostr.* depressum, *apice* unguiculato, inferne bursa instructum.	Onocrotalus.
	Cygnus.	*Rostr.* conico-convexum.	Olor. Elder. Anser. Ans. Bernicla.
	Anas.	*Rostr.* conico-depressum.	Anas fera. Glaucium. Boschas. *A. Domest.* Penelope. Querquedula.
	Mergus.	*Rostr.* cylindriforme, *apice* adunco.	Mergus. Merganser.
	Graculus.	*Rostr.* conicum, *apice* adunco.	Carbo aquat. Graculus aquat.
	Colymbus.	*Rostr.* subulatum. *Pedes* infra æquilibr.	Colymbus. C. minim. Podiceps. Arctica.
	Larus.	*Rostr.* subulatum. *Pedes* in æquilibr.	Cataracta. Larus. Sterna. Piscator.
SCOLOPACES. *Rostrum* cylindraceo-tereiusculum.	Hæmatopus.	*Pes* 3dact. *Rostri* apex compressus.	Pica marina.
	Charadrius.	*Pes* 3dact. *Rostri* apex teres.	Pluvialis. Hiaticula.
	Vanellus.	*Pes* 4dact. *Rostrum* digitis brevius. *Caput* pennato cristatum.	Capella.
	Tringa.	*Pes* 4dact. *Rostrum* digitis brevius. *Caput* simplex.	Tringa. Ocrophus. Pugnax. Gallinula.
	Numenius.	*Pes* 4dact. *Rostrum* digitis longius.	Gallinago. Limosa. Arquata. Recurvirostra.
	Fulica.	*Pes* 4dact. *Digiti* membranis aucti. *Caput* carnoso-cristatum.	Gallinula aquatica.
GALLINÆ. *Rostrum* conico-incurvum.	Struthio.	*Pes* 2dact. absque postico.	Struthio-camelus.
	Casuarius.	*Pes* 3dact. absque postico. *Caput* galea & palearibus ornatum.	Emeu.
	Otis.	*Pes* 3dact. absque postico. *Caput* simplex.	Tarda.
	Pavo.	*Pes* 4dact. *Caput* corolla pennac. orn.	Pavo.
	Meleagris.	*Pes* 4dact. *Frons* papilla. *Gula* membrana unica longitudinali instructa.	Gallopavo.
	Gallina.	*Pes* 4dact. *Frons* membrana serrata. *Gula* membr. duplici longitud. inst.	Gallina.
	Tetrao.	*Pes* 4dact. *Supercilia* papillosa nuda.	Phasianus. Urogallus. Tetrao. Bonasia. Lagopus. Perdix. Coturnix.
PASSERES. *Rostrum* conico-attenuatum.	Columba.	*Rostr.* rectum, ad basin surfuraceum. *Nares* oblongæ, membranula superne instructæ.	Columba. Turtur. Palumbus. Oenas.
	Turdus.	*Rostr.* parum convexum. *Pluma* rostri basin tegunt.	Turdus. Merula.
	Sturnus.	*Rostr.* rectum subteres. *Lingua* bifida cornea.	Sturnus.
	Alauda.	*Unguis* digiti postici digitis ipsis longior.	Alauda.
	Motacilla.	*Rostr.* gracile. *Fauces* nigricant. *Lingua* apex bifidus laceratus.	Motacilla. Oenanthe. Merula aquatica.
	Luscinia.	*Rostr.* gracile rectum. *Lingua* apex bifidus laceratus.	Luscinia. Ficedula. Erithacus. Troglodytes. Carolina *Rudb.*
	Parus.	*Rostr.* gracile. *Lingua* apex truncatus, 4 setis instructus.	Parus. P. caudatus. . . . cristatus.
	Hirundo.	*Rostr.* gracile, ad basin depressum, minimum: *rictu* amplissimo.	Hirundo. Caprimulgus.
	Loxia.	*Rostr.* crassum, magnum, breve, curvum, undique convexum.	Coccothraustes. Loxia. Pyrrhula.
	Ampelis.	*Rostr.* crassum, rectum. *Remigum* apices nonnulli membranacei.	Garrulus Bohem.
	Fringilla.	*Rostr.* crassum. *Maxilla* utraque alteram sinu quodam ad basin recipit.	Fringilla. Carduelis. Emberiza. Spinus. Passer.

III. AMPHIBIA.

Corpus nudum, vel squamosum. *Dentes molares* nulli: *reliqui* semper. *Pinnæ* nullæ.

SERPENTIA.	Testudo.	*Corpus* quadrupedium, caudatum, testa munitum.	Testudo tessulata. . . . . terrestris. . . . . marina. Lutaria.
	Rana.	*Corpus* quadrupedium, cauda destitutum, squamis carens.	Bufo. Rana arborea. . . aquatica. . . Carolina.
	Lacerta.	*Corpus* quadrupedium, caudatum, squamosum.	Crocodilus. Allegator. Cordylus. Draco volans. Scincus. Salamandra aq. . . terrestris. Chamæleo. Seps. Senembi *Mrg.*
	Anguis.	*Corpus* apodum, teres, squamosum.	Vipera. Cæcilia. Aspis. Caudisona. Cobras de Cabelo. Anguis Æsculapii. Cenchris. Natrix. Hydrus.

AMPHIBIORUM Classem ulterius continuare noluit benignitas Creatoris; Ea enim si tot Generibus, quot reliquæ Animalium Classes comprehendunt, gauderet; vel si vera essent quæ de Draconibus, Basiliscis, ac ejusmodi monstris οἱ τερατολόγοι fabulantur, certè humanum genus terram inhabitare vix posset.

PARADOXA.

HYDRA corpore anguino, pedibus duobus, collis septem, & totidem capitibus, alarum expers, asservatur Hamburgi, similitudinem referens Hydræ Apocalypticæ à S. JOANNE CAP. XII. & XIII. descriptæ. Eaque tanquam veri animalis speciem plurimis præbuit, sed falso. Natura sibi semper similis plura capita in uno corpore nunquam produxit naturaliter. Fraudem & artificium, cum Ipsi vidimus, dentes Ferino-mustelini, ab Amphibiorum dentibus diversi, facillime detexerunt.

RANA-PISCIS s. RANÆ IN PISCEM METAMORPHOSIS valdè paradoxa est, quum Natura mutationem Generis unius in aliam diversæ Classis non admittat. Ranæ, ut Amphibia omnia, pulmonibus gaudent & ossibus spinosis. Pisces spinosi, loco pulmonum, branchiis instruuntur. Ergo legi Naturæ contraria foret hæc mutatio. Si enim piscis hic instructus est branchiis, erit diversus à Rana & Amphibiis. Si verò pulmones, erit Lacerta: nam toto cælo à Chondropterygiis & Plagiuris differt.

MONOCEROS *Veterum*, corpore equino, pedibus ferinis cornu recto, longo, spiraliter intorto, Pictorum figmentum est. MONODON *Artedi* ejusmodi cornu gerit, cæteri verò partibus multum differt.

PELECANUS rostro vulnus infligens femori suo, ut emanante sanguine sitim pullorum levet, fabulosè ab Iisdem traditur. Ansam fabulæ dedit saccus sub gula pendulus.

SATYRUS caudatus, hirsutus, barbatus, humanum referens corpus, gesticulationibus valde deditus, salacissimus Simiæ species est, si unquam aliquis visus fuit. *Homines* quoque *Caudati*, de quibus recentiores peregrinatores multa narrant, ejusdem generis sunt.

BOROMETZ s. AGNUS SCYTHICUS plantis accensetur, & agno adsimilatur; cui caulis alterius plantæ è terra erumpens umbilicum intrat; idemque sanguine præditus à feris devorari temerè dicitur. Est autem artificiosè ex radicibus Filicinis Americanis compositus. Naturaliter autem est *Embryo Ovis* allegoricè descriptus, qui omnia data habet attributa.

PHOENIX, Avis species, cujus unicum in mundo individuum, & quæ decrepita ex ferali busto, quod sibi ex aromatibus struxerat, repuerascere fabulosè fertur, felicem subitura prioris vitæ periodum. Est verò PALMA DACTYLIFERA. vid. *Kæmpf.*

BERNICLA s. ANSER SCOTICUS & CONCHA ANATIFERA è lignis putridis in mare abjectis nasci à Veteribus creditur. Sed fucum imposuit *Lepas* interaneis suis penniformibus, & modo adhærendi, quasi verus ille anser *Bernicla* inde oriretur.

DRACO corpore anguino, duobus pedibus, duabus alis Vespertilionis instar, est *Lacerta alata*, vel *Raja* per artem monstrosè ficta, & siccata.

AUTOMA MORTIS Horologii minimi sonitum edens in parietibus, est *Pediculus pulsatorius* dictus, qui ligna perforat, eaque inhabitat.

IV PISCES.

Corpus apodum, pinnis veris instructum, nudum, vel squamosum.

PLAGIURI. *Cauda* horizontalis.	Thrichechus.	*Dentes* in utraque maxilla. *Dorsum* impenne.	Manatus s. *Vacca mar.*
	Catodon.	*Dentes* in inferiore maxilla. *Dorsum* impenne.	Cot. Fistula in rostro *Art.* Cete *Clus.*
	Monodon.	*Dens* in superiore max. 1. *Dorsum* impenne.	Monoceros. *Unicornu.*
	Balæna.	*Dentes* in sup. max. cornei. *Dorsum* sæpius impenne.	B. Groenland. B. Finfisch. B. Maxill. inf. latiore. *Art.*
	Delphinus.	*Dentes* in utraque maxilla. *Dorsum* pinnatum.	Orcha. Delphinus. Phocæna.
CHONDROPTERYGII. *Pinnæ* cartilagineæ.	Raja.	*Foramina* branch. utrinq. 5. *Corpus* depressum.	Raja clav. asp. læv. &c. Squatino-Raja. Altavela. Pastinaca mar. Aquila. Torpedo. Bos *Vet.*
	Squalus.	*Foram.* branch. utrinq. 5. *Corpus* oblongum.	Lamia. Galeus. Catulus. Vulpes mar. Zygæna. Squatina. Centrine. Pristis.
	Acipenser.	*Foram.* branch. utrinq. 1. *Os* edentul. tubulatum.	Sturio. Huso. *Ichthyocolla.*
	Petromyzon.	*Foram.* branch. utrinq. 7. *Corpus* bipenne.	Enneophthalmus. Lampetra. Mustela.
BRANCHIOSTEGI. *Pinnæ* offic. carentes. *Branch.* off. & membran.	Lophius.	*Caput* magnitudine corporis. *Appendices* horizontaliter latera piscis ambiunt.	Rana piscatrix. Guacucuja.
	Cyclopterus.	*Pinnæ* ventrales in unicam circularem concretæ.	Lumpus. *Lepus mar.*
	Ostracion.	*Pinnæ* ventrales nullæ. *Cutis* dura, sæpe aculeata	Orbis div. sp. Pisc. triangul. Atinga. Hystrix. Ostracion. Lagocephalus.
	Balistes.	*Dentes* contigui maximi. *Aculei* aliquot robusti in dorso.	Guaperua. Histrix. Capriscus. *Caper.*
ACANTHOPTERYGII. *Pinnæ* osseæ, quarum quædam aculeatæ.	Gasterosteus.	*Membr. branch.* ossiculis 3. *Venter* laminis osseis instr.	Aculeatus. Spinachia. Pungitius.
	Zeus.	*Corpus* compressum. *Squamæ* subasperæ.	Aper. Faber. *Gallus mar.*
	Cottus.	*Membrana branch.* offic. 6. *Caput* aculeatum, corpore latius.	Cataphractus. Scorpio mar. Cottus. *Gobio fl. capit.*
	Trigla.	*Appendices* ad pinn. pect. articulatæ 2 vel 3.	Lyra. Gurnardus. Cuculus. Lucerna. Hirundo. Milvus. Mullus barb. & imberb.
	Trachinus.	*Operula branch.* aculeata. *Oculi* vicini in vertice.	Draco. Araneus mar. Uranoscopus.
	Perca.	*Memb. branch.* officul. 7. *Pinnæ* dorsales. 1 vel 2.	Perca. Lucioperca. Cernua. Schraitser.
	Sparus.	*Opercula branch.* squamosa. *Labia* dentes tegunt. *Dentes* molares obtinet.	Salpa. Melanurus. Sparus. Sargus. Chromis. Mormyrus. Mæna. Smaris. Boops. Dentex. Erythrinus. Pagrus. Aurata. Cantharus.
	Labrus.	*Labia* crassa dentes teg. *Color* speciosus.	Julis. Sachettus. Turdus diversar. specier.
	Mugil.	*Memb. branch.* offic. 6. *Caput* totum squamosum.	Mugil. *Cephalus.*
	Scomber.	*Memb. branch.* offic. 7. *Pinnæ dorsi* 2 vel plures.	Glaucus. Amia. Scomber. Thynnus. Trachurus. *Saurus.*
	Xiphias.	*Rostrum* apice ensiformi. *Pinnæ ventrales* nullæ.	Gladius.
	Gobius.	*Pinnæ vent.* in 1 simpl. concr. *Squamæ* asperæ.	Gob. niger. Jozo. Paganellus. *Aphua.*
MALACOPTERYGII. *Pinnæ* osseæ, quæ omnes molles.	Gymnotus.	*Membr. branch.* officul. 5. *Pinna* dorsalis nulla.	Carapo.
	Muræna.	*Membr. branch.* offic. 10. *Tubuli* in apice rostri. 2.	Anguilla. Conger. Fluta. Serpens mar.
	Blennus.	*Pinnæ ventr.* constant oss. 2. *Caput* admodum declive.	Alauda non crist. & galer. Blennus. Gattorugine.
	Gadus.	*Membr. branch.* offic. 7. *Pinnæ* dorsi. 2 vel 3.	Asellus diversar. specier. Merluccius. Anthias adus. Mustela. Egrefinus.
	Pleuronectes.	*Membr. branch.* off. 6. *Oculi* ambo in eodem later.	Rhombus divers. specier. Passer. Limanda. Hippoglossus. Bugloss. Solea.
	Ammodytes.	*Membr. branch.* offic. 7. *Pinnæ* ventr. nullæ.	Ammodytes. *Tobianus.*
	Coryphæna.	*Membr. branch.* offic. 5. *Pinna* dorsi à capite ad caudam.	Hippurus. Pompilus. Novacula. *Pesce.*
	Echeneis.	*Striæ* transversæ, asperæ, in superna capitis parte.	Remora.
	Esox.	*Membr. branch.* offic. 14.	Lucius. Belone. Acus maxima squamosa.
	Salmo.	*Membr. branch.* offic. 10-12. *Corpus* maculosum.	Salmo. Trutta. Umbla. Carpio lacustr.
	Osmerus.	*Membr. branch.* offic. 7--8. *Dentes* in max. lingu. palat.	Eperlanus. *Spirinchus.* Saurus.
	Coregonus.	*Membr. branch.* offic. 8--10. *Appendix* pinniformis.	Albula. *Lavaretus.* Thymallus. Oxyrhynchus.
	Clupea.	*Membr. branch.* offic. 8. *Venter* acutus serratus.	Harengus. Spratti. Encrasicholus. Alosa.
	Cyprinus.	*Membr. branch.* offic. 3. *Dentes* ad orificium ventriculi tantum.	Erythrophthal. Mugil. fluv. Brama. Ballerus. Capito. Nasus. A. M. Carassius. Cypr. nobilis. Tinca. Barbus. Rutilus. Alburnus. Leuciscus. Phoxinus. Gobius fl.
	Cobitus.	*Caput* compressum. *Pinnæ* dorsi & ventrales eâdem à rostro distantia.	Cobitis. Barbatula. Misgurn.
	Syngnathus.	*Opercula branch.* ex lamina 1. *Maxilla* à lateribus clausæ.	Acus lumbr. Acus *Aristot.* Hippocampus.

V. INSECTA.

Corpus crusta ossea cutis loco tectum. *Caput* antennis instructum.

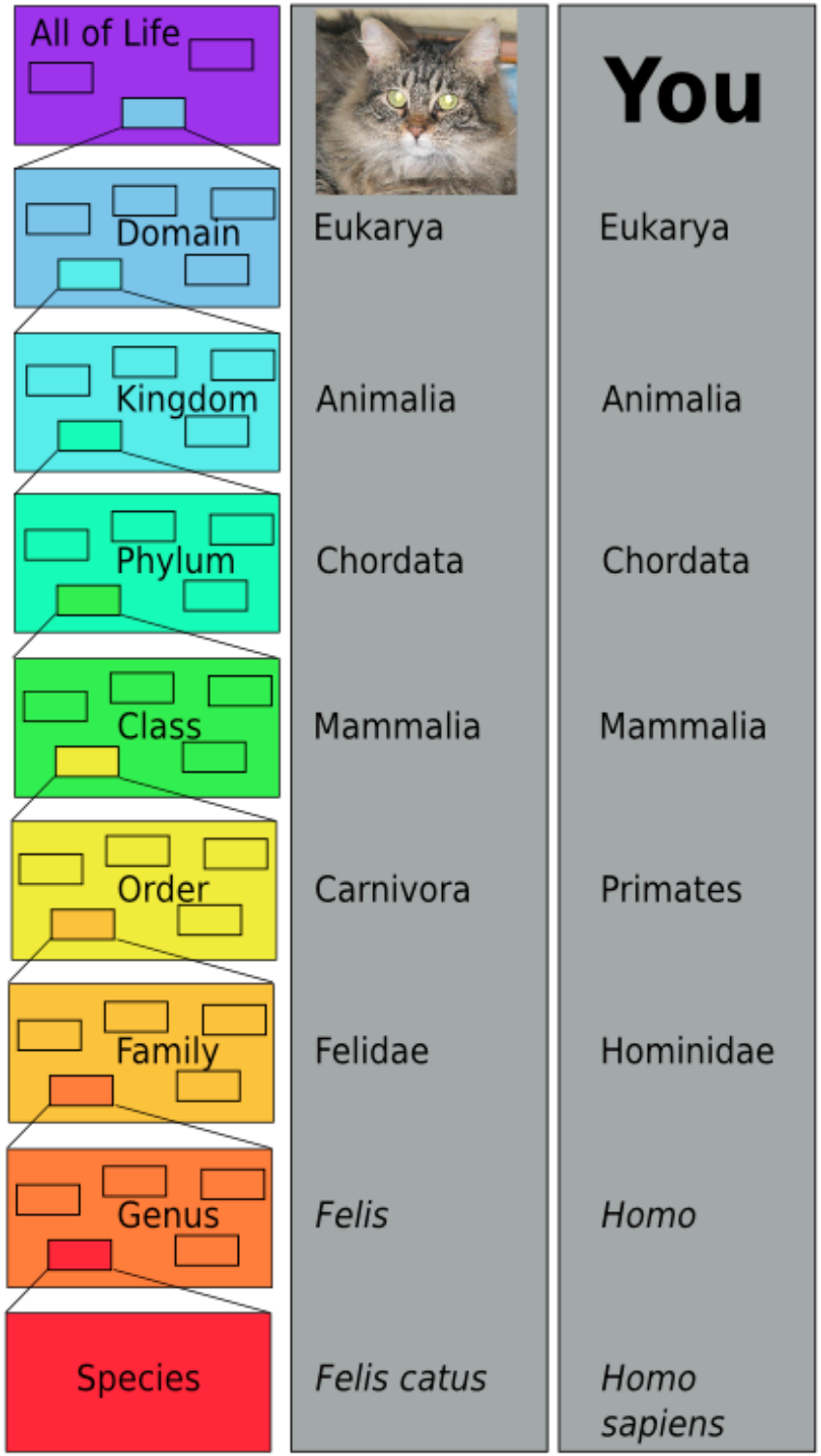
COLEOPTERA. *Alæ* elytris duobus tectæ.	Blatta.	§. FACIE EXTERNA FACILE DISTING. *Elytra* concreta. *Alæ* nullæ. *Antennæ* truncatæ.	Scarab. tardipes. Blatta fœtida.
	Dytiscus.	*Pedes* postici remorum forma & usu. *Ant.* setaceæ. *Sterni* apex bifurcus.	Hydrocantharus. Scarab. aquaticus.
	Meloë.	*Elytra* mollia, flexilia, corpore breviora. *Ant.* moniliformes. *Ex* articulis oleum fundens.	Scarab. majalis. Scarab. unctuosus.
	Forficula.	*Elytra* brevissima, rigida. *Cauda* bifurca.	Staphylinus. Auricularia.
	Notopeda.	Positum in dorso *exsilit. Ant.* capillaceæ.	Scarab. elasticus.
	Mordella.	*Cauda* aculeo rigido simplici armata. *Ant.* setaceæ, breves.	Negatur ab *Aristotele.*
	Curculio.	*Rostrum* productum, teres, simplex. *Ant.* clavatæ in medio Rostri positæ.	Curculio.
	Buceros.	*Cornu* 1. simplex, rigidum, fixum. *Ant.* capitatæ, foliaceæ.	Rhinoceros. Scarab. monoceros.
	Lucanus.	*Cornua* 2. ramosa, rigida, mobilia. *Ant.* capitatæ, foliaceæ.	Cervus volans.
	Scarabæus.	§. ANTENNÆ TRUNCATÆ. *Ant.* clavatæ foliaceæ. *Cornua* nulla.	Scarab. pilularis. Melolontha. Dermestes.
	Dermestes.	*Ant.* clavatæ horizontaliter perfoliatæ. *Clypeus* planiusculus, emarginatus.	Cantharus fasciatus.
	Cassida.	*Ant.* clavato-subulatæ. *Clypeus* planus, antice rotundatus.	Scarab. clypeatus.
	Chrysomela.	*Ant.* simplices, clypeo longiores. *Corpus* subrotundum.	Cantharellus.
	Coccionella.	*Ant.* simplices, brevissimæ: *Corpus* hemisphæricum.	Cochinella vulg.
	Gyrinus.	*Ant.* simplices. *Corpus* breve. *Pedibus* posticis saliens.	Pulex aquaticus. Pulex plantarum.
	Necydalis.	*Ant.* clavato-productæ. *Clypeus* angustus, rotundatus.	Scarabæo-formica.
	Attalabus.	*Ant.* simplices, constructæ articulis orbicularibus, præter ultim. globosum.	Scarab. pratensis.
	Cantharis.	§. ANTENNÆ SETACEÆ. *Clypeus* planus, margine undique promin. *Elytra* flexilia.	Cantharis *offic.*
	Carabus.	*Clypeus* fere planus, marg. prominente. *Elytra* fragilia.	Cantharus fœtidus. Cantharellus auratus.
	Cicindela.	*Clypeus* cylindraceus vel teres. *Forceps* oris prominens.	Cantharus Marianus.
	Leptura.	*Clypeus* subrotundus. *Pedes* longi. *Corpus* tenue acuminatum.	Scarab. tenuis.
	Cerambyx.	*Clypeus* ad latera mucrone prominet. *Ant.* corpus longitudine æquant, vel superant.	Capricornus.
	Buprestis.	*Clypeus* superne 2 punctis elevatis notatus.	Scarab. sylvaticus.
ANGIOPTERA. *Alæ* omnibus datæ, elytris destitutæ.	Papilio.	*Rostrum* spirale. *Alæ* 4.	Papilio alis erectis. Psyche - - - planis. Phalæna -- compressis.
	Libellula.	*Cauda* foliosa. *Alæ* 4. expansæ.	Perla. Virguncula.
	Ephemera.	*Cauda* setosa. *Alæ* 4. erectæ.	Musca Ephemera.
	Hemerobius.	*Cauda* setosa. *Alæ* 4. compressæ.	Phryganea.
	Panorpa.	*Cauda* cheliformis. *Alæ* 4. *Rostr.* corn.	Musca scorpiurus.
	Raphidia.	*Cauda* spinoso-setacea. *Alæ* 4. *Cap.* corn.	*Non descripta.*
	Apis.	*Cauda* aculeo simplici. *Alæ* 4.	Crabro. Vespa. Bombylius. Apis.
	Ichneumon.	*Cauda* aculeo partito. *Alæ* 4.	Ichneumon. Musca tripilis.
	Musca.	*Stylus* sub alis capitatus. *Alæ* 2.	Muscæ div. spec. Oestrum *Vet.* Oestrum *Lapponum.* Tabanus. Culex. Teredo nav. Tipula. Formica-leo.
HEMIPTERA. *Alæ* elytris destitutæ; Quibusdam tantum individuis concessæ.	Gryllus.	*Pedes* 6. *Alæ* 4. *superiores* crassiores.	Gryllus domesticus. Gryllo-talpa. Locusta. Mantis.
	Lampyris.	*Pedes* 6. *Clypeus* planus. *Alæ* 4.	Cicindela.
	Formica.	*Pedes* 6. *Alæ* 4. *Cauda* aculeum condit.	Formica.
	Cimex.	*Pedes* 6. *Alæ* 4. cruciferæ. *Rostrum* styliforme, rectum.	Cimex lectularius. Orsodachne. Tipula aquatica. Bruchus.
	Notonecta.	*Pedes* 6. quorum *postici* remorum figura & usu. *Alæ* 4. cruciferæ.	Notonecta aquatica.
	Nepa.	*Pedes* 4. *Frons* chelifera. *Al.* 4. crucif.	Scorpio aquat.
	Scorpio.	*Pedes* 8. *Frons* chelifera, aculeata. *Alæ* 4. laxæ.	Scorpio terrestris.
APTERA. *Alæ* nullæ.	Pediculus.	*Pedes* 6. *Antennæ* capite breviores.	Pediculus humanus. Ped. avium. Ped. piscium. Ped. pulsatorius.
	Pulex.	*Pedes* 6. saltatrices.	Pulex vulgaris.
	Monoculus.	*Pes* 1.? *Antennæ* bifidæ.	Pulex arboresc. *Swam.* *Monoculus Bradl.* *Apus Frisch.*
	Acarus.	*Pedes* 8. articulis 8 constantes. *Oculi* 2. *Ant.* minimæ.	Ricinus. Scorpio-araneus. Pedic. inguinalis. Pedic. Scarabæi. Pedic. Scabiei. Araneus coccineus.
	Araneus.	*Pedes* 8. *Oculi* communiter 8.	Araneus. Tarantula. Phalangium.
	Cancer.	*Pedes* 12. *priores* cheliformes.	Cancer. Astacus. Pagurus. Squilla. Majas. Eremita. Gammarus.
	Oniscus.	*Pedes* 14.	Asellus *Offic.* Asellus aquat.
	Scolopendria.	*Pedes* 20. & ultra.	Scolop. terrestris. Scolop. marina. Julus.

VI. VERMES.

Corporis *Musculi* ab una parte basi cuidam solidæ affixi.

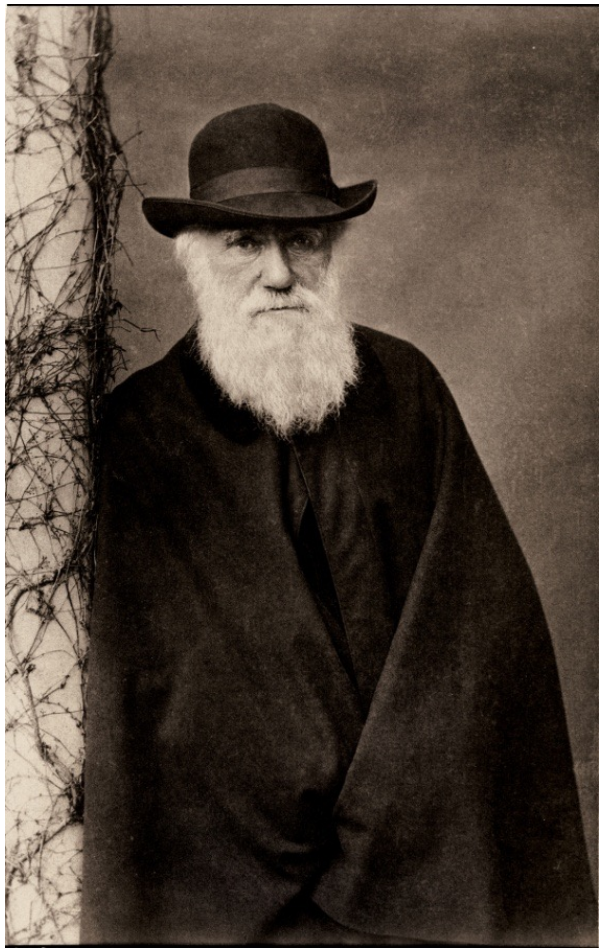
REPTILIA. Nuda, artubus destituta.	Gordius.	*Corpus* filiforme, teres, simplex.	Seta aquatica. Vena Medina.
	Tænia.	*Corpus* fasciatum, planum, articulatum.	Lumbricus longus.
	Lumbricus.	*Corpus* teres, annulo prominenti cinctum.	Intestinum terræ. Lumbricus latus. Ascaris.
	Hirudo.	*Corpus* inferne planum, superne convex. tentaculis destitutum.	Sanguisuga.
	Limax.	*Corpus* inferne planum, superne conv. tentaculis instructum.	Limax.
TESTACEA. Habitaculo Lapideo instructa.	Cochlea.	*Testa* univalvis, spiralis, unilocularis.	Helix. Labyrinthus. Voluta. Cochlea varia. Buccinum. Lyra. Turbo. Cassida. Strombus. Fistula. Terebellum. Murex. Purpura. Aporrhais. Nerita. Trochus.
	Nautilus.	*Testa* univalvis, spiralis, multilocularis.	Nautilus. Orthoceros. Lituus.
	Cypræa.	*Testa* univalvis, convoluta, rima longitudinali.	Concha Veneris. Porcellana.
	Haliotis.	*Testa* univalvis, patula, leviter concava, perforata, ad angulum spiralis.	Auris marina.
	Patella.	*Testa* univalvis, concava, simplex.	Patella.
	Dentalium.	*Testa* univalvis, teres, simplex.	Dentalium. Entalium. Tubus vermicul.
	Concha.	*Testa* bivalvis.	Mytulus. Vulva marina. Pholas. Bucardium. Perna. Chama. Solenes. Tellina. Pinna. Ostrea. Pecten. Mitella. *Vomer.*
	Lepas.	*Testa* multivalvis. *Valvulæ* duabus plures.	Concha anatifera. Verruca testudin. Balanus marinus.
ZOOPHYTA. Artubus donata.	Tethys.	*Corpus* forma variabile, molle, nudum.	Tethya. Holothurium. Penna marina.
	Echinus.	*Corpus* subrotundum, testa tectum, aculeis armatum.	Echinus marinus.
	Asterias.	*Corpus* radiatum, corio tectum, scabrum.	Stella marina. Stella oligantis. St. pentactinoides. St. polyactinoid.
	Medusa.	*Corpus* orbiculatum, gelatinosum, subtus filamentosum.	Urtica marina. Urt. vermiformis. Urt. crinita. Urt. astrophyta.
	Sepia.	*Corpus* oblongum, interne osseum, anterius octo artubus donatum.	Sepia. Loligo.
	Microcosmus.	*Corpus* variis heterogeneis tectum.	Microcosm. marin.

Taxonomy today

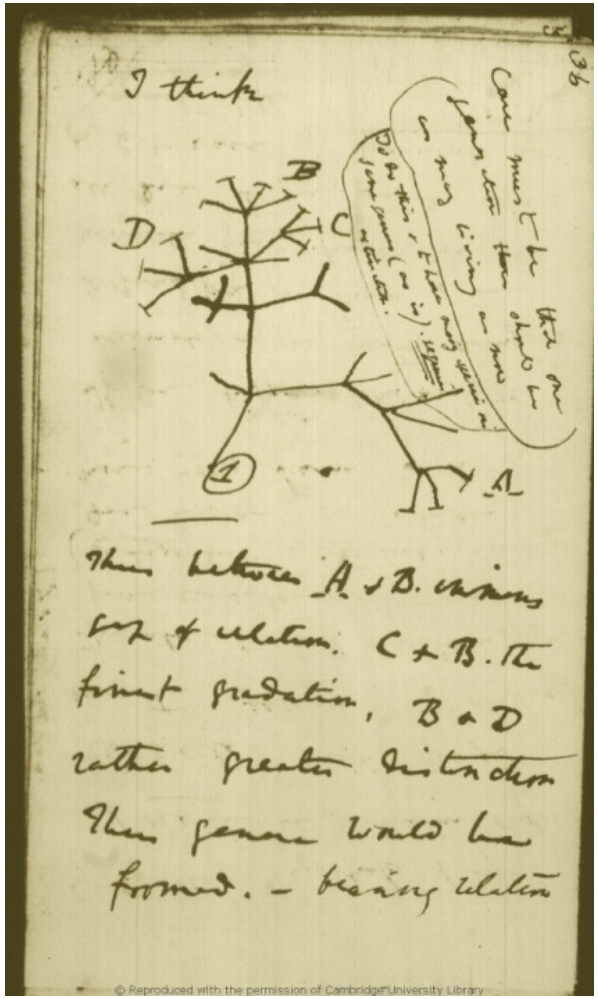


study.com

Darwinian theory of evolution



Charles Darwin (1809-1882)



Darwin's sketch of the tree of life

Fundamental insight: species that have more similar traits have a more recent common ancestor.

Provides a rationale for the similarity relationship of species.

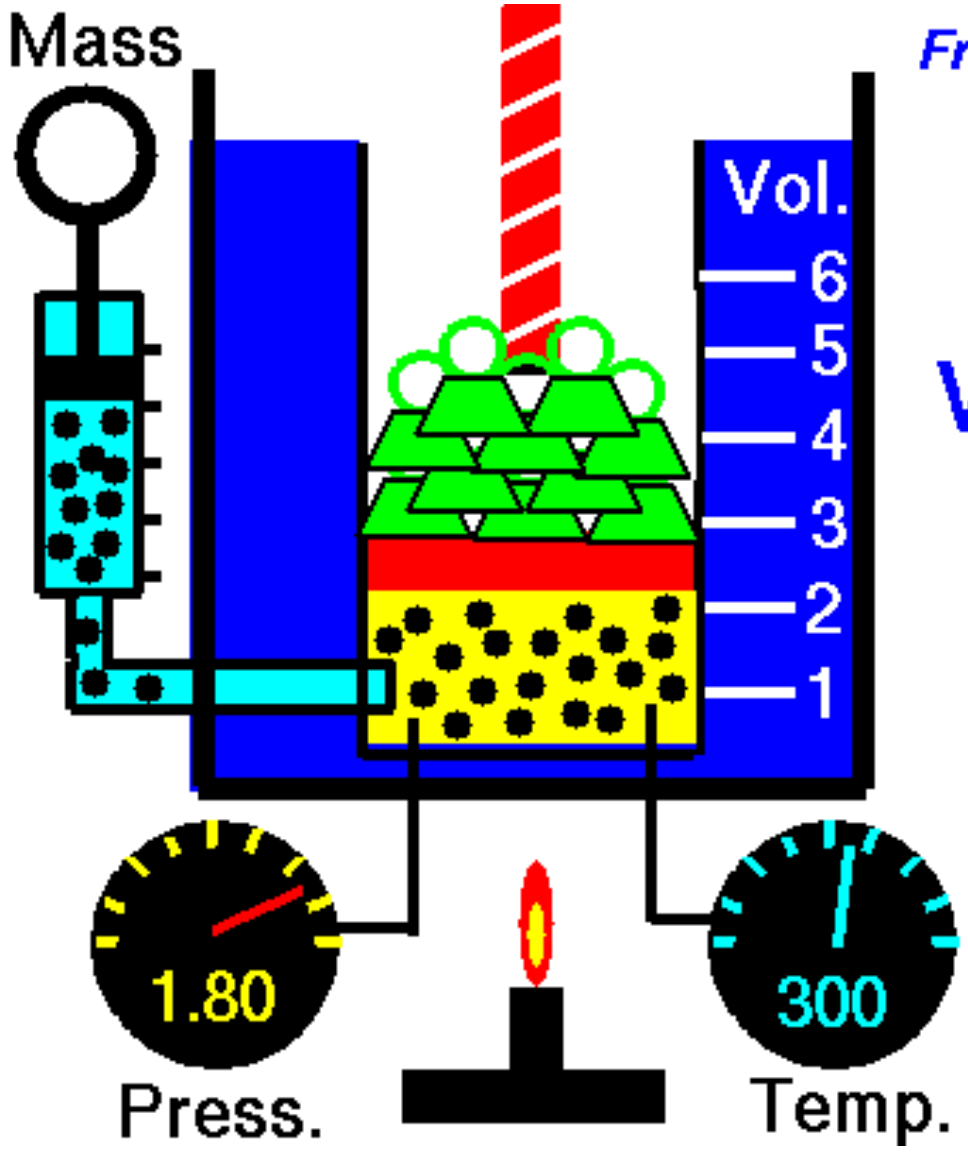
The internal nodes of the tree represent species that really existed.

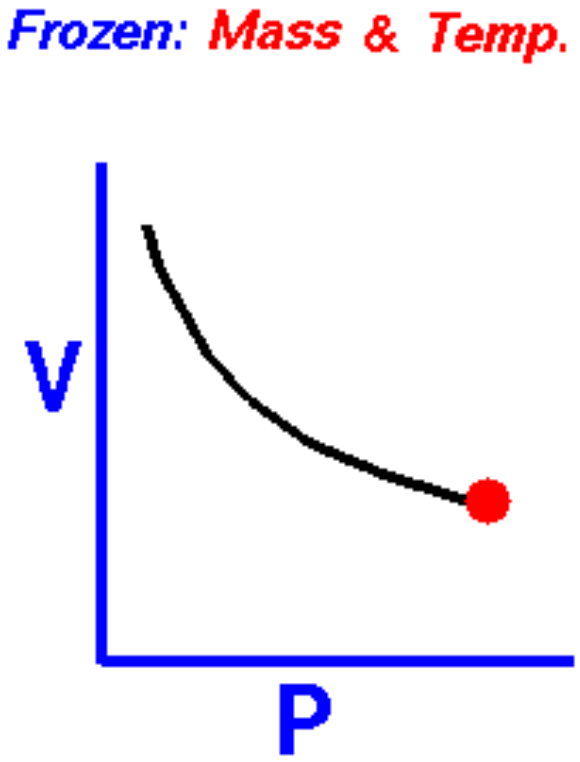
- Big conceptual jump
- Not a quantitative law

Capturing relationships in natural phenomena

Boyle's law

P * V = k if mass and temperature are constant



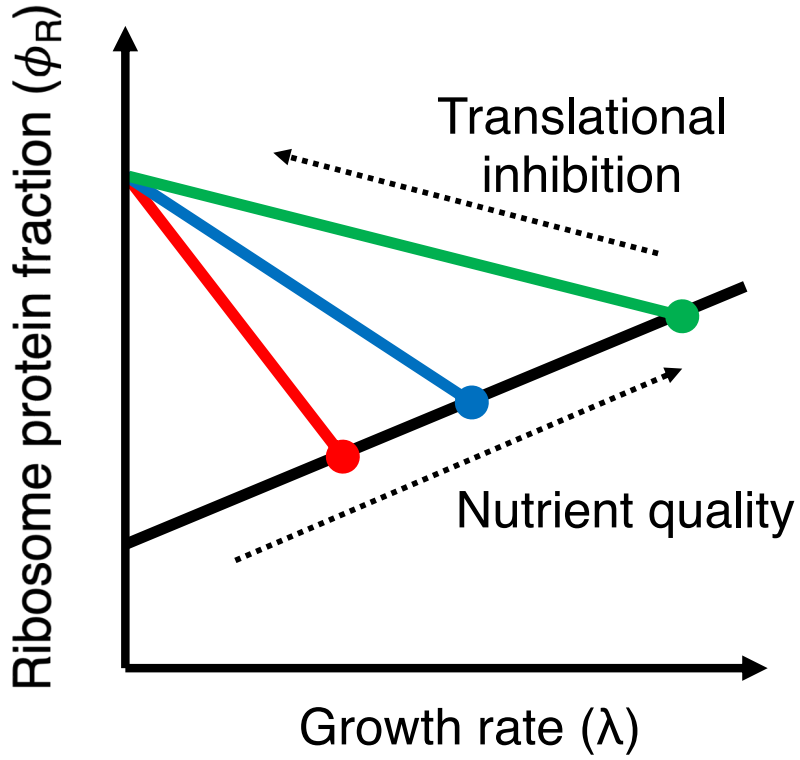


Named after Robert Boyle, who published the original law in 1662

wikimedia.org

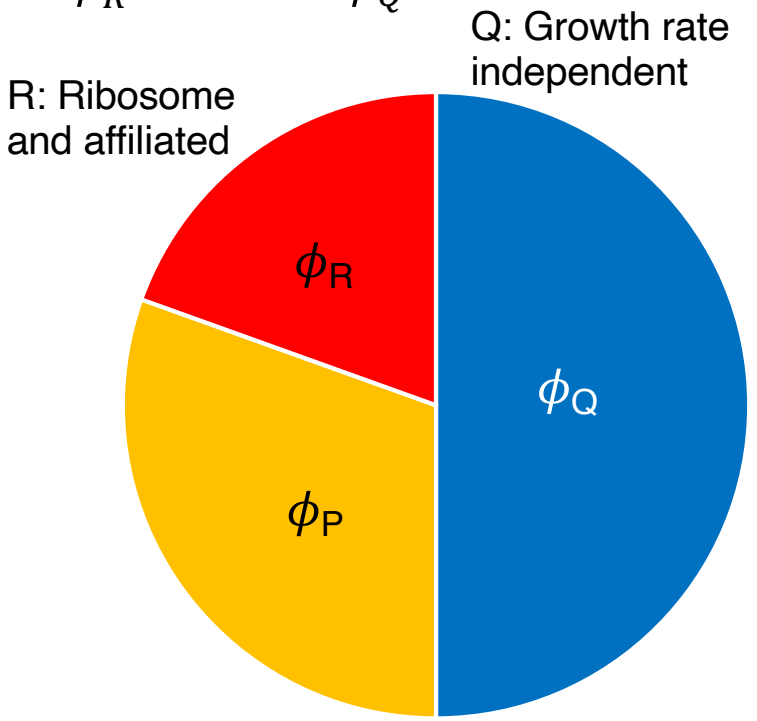
Macroscopic laws in resource allocation

Empirical growth laws in bacteria



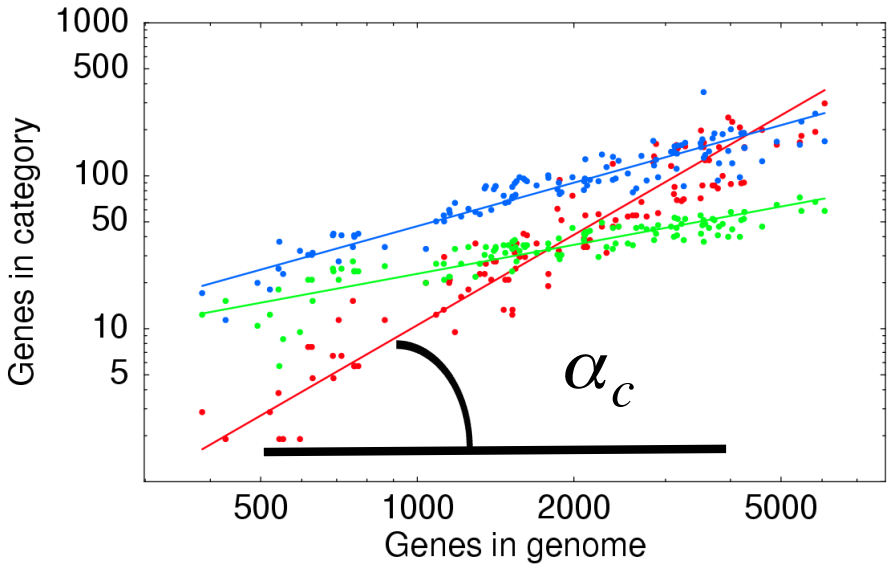
Matthew Scott, Terry Hwa (e.g. MSB 2014)

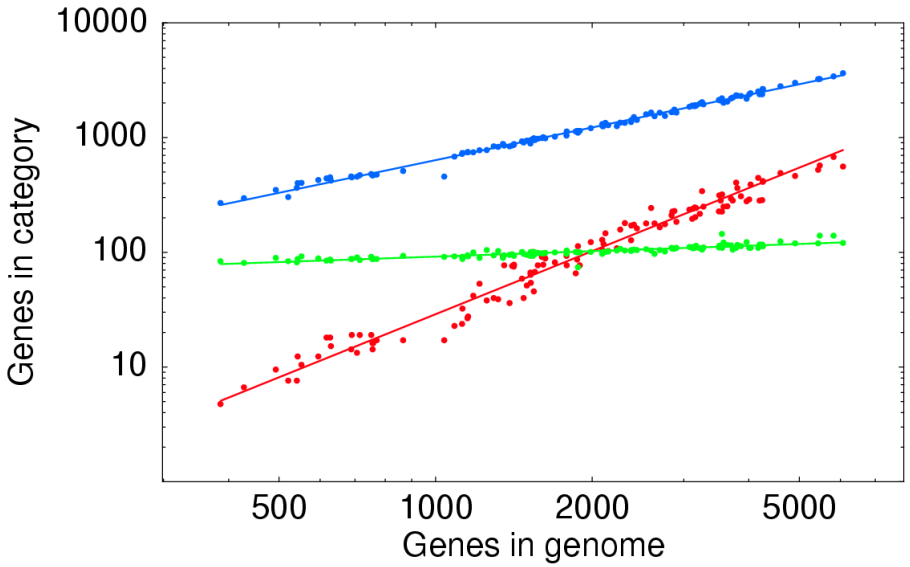
$$\varphi_P + \varphi_R = \varphi_R^{max}$$
$$\varphi_R^{max} = 1 - \varphi_Q$$



P: Metabolic fraction (anabolism/catabolism)

Empirical laws of genome composition



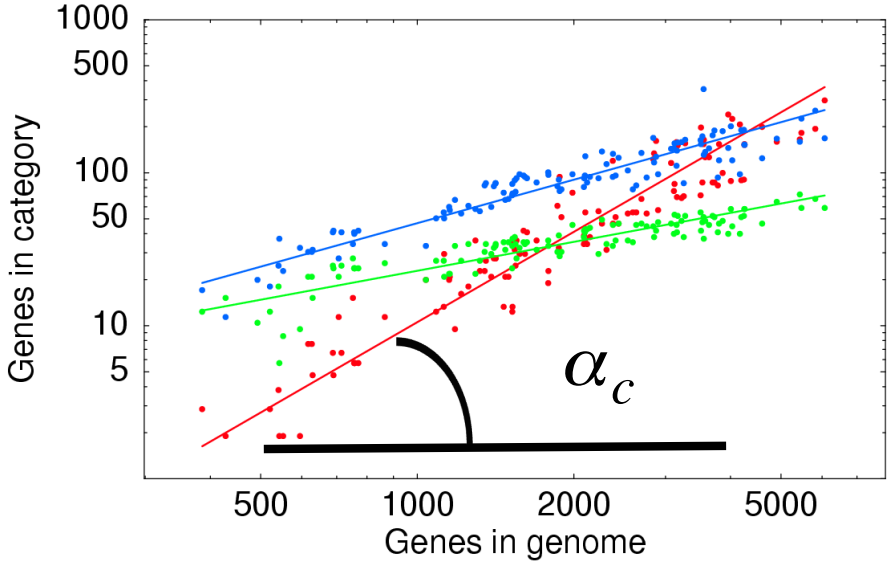


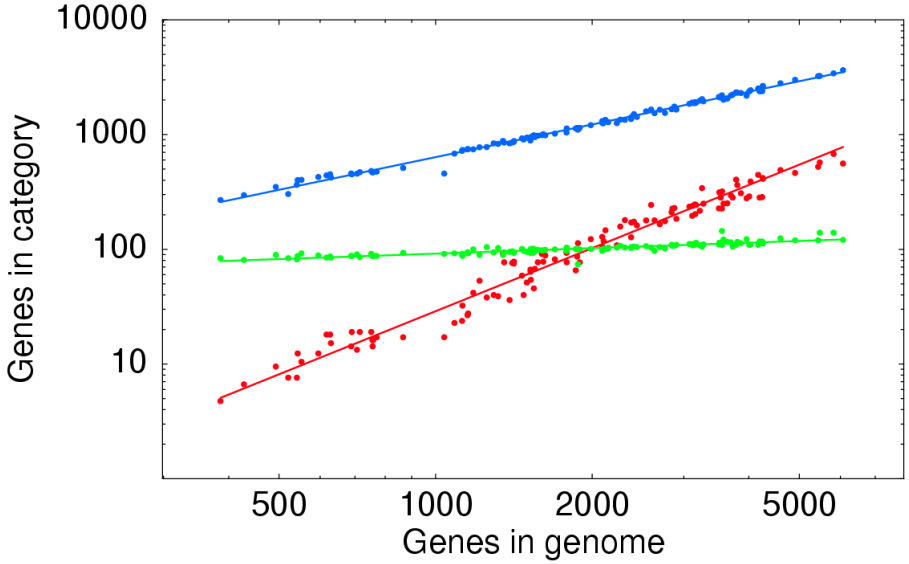
Left panel		Right Panel	
Signal transduction	1.95 +/-0.15	Transcription regulation	1.83+/-0.12
Carbohydrate metabolism	0.94+/-0.1	Biological process	0.94+/-0.04
DNA repair	0.63+/-0.07	Protein biosynthesis	0.15+/-0.03

$$n_c = A_c n^{\alpha_c} \Leftrightarrow \log(n_c) = C_c + \alpha_c \log(n)$$

van Nimwegen E. Trends in Genetics (2003)

Empirical laws of genome composition





Left panel		Right Panel	
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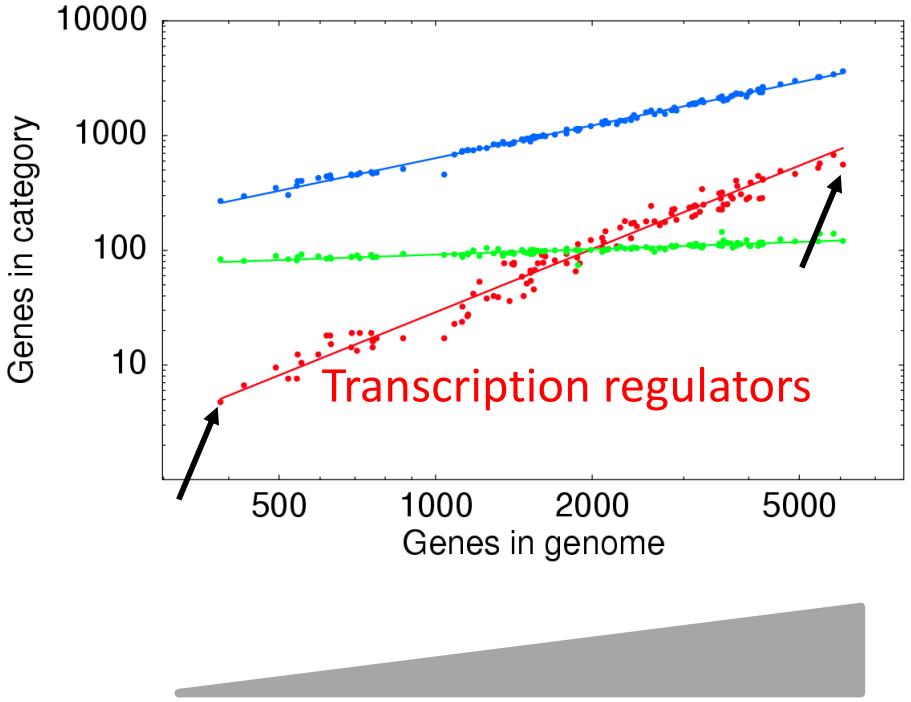
Carbohydrate metabolism	0.94+/-0.1	Biological process	0.94+/-0.04
DNA repair	0.63+/-0.07	Protein biosynthesis	0.15+/-0.03

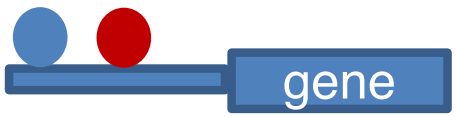
These relationships tell us something about the organization of living entities and the constraints on it.

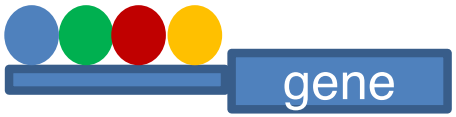
Empirical laws of genome composition

$$n_R \langle targets\ per\ regulator \rangle = n_G \langle regulatory\ inputs \rangle$$

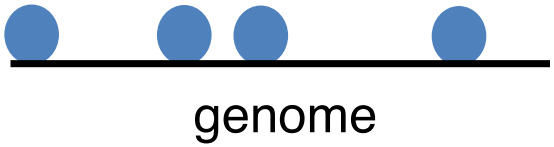
$$\frac{n_R}{n_G} = \frac{\langle regulatory\ inputs\ per\ gene \rangle}{\langle targets\ per\ regulator \rangle}$$

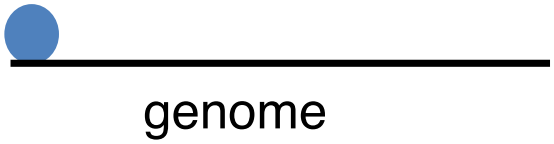






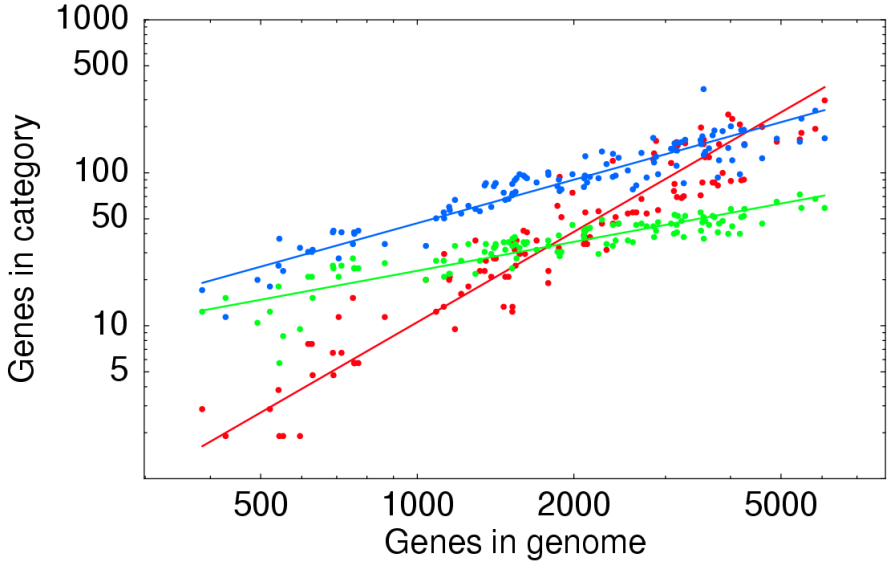
$$\frac{n_R}{n_G} = \frac{\langle regulatory\ inputs\ per\ gene \rangle}{\langle targets\ per\ regulator \rangle}$$

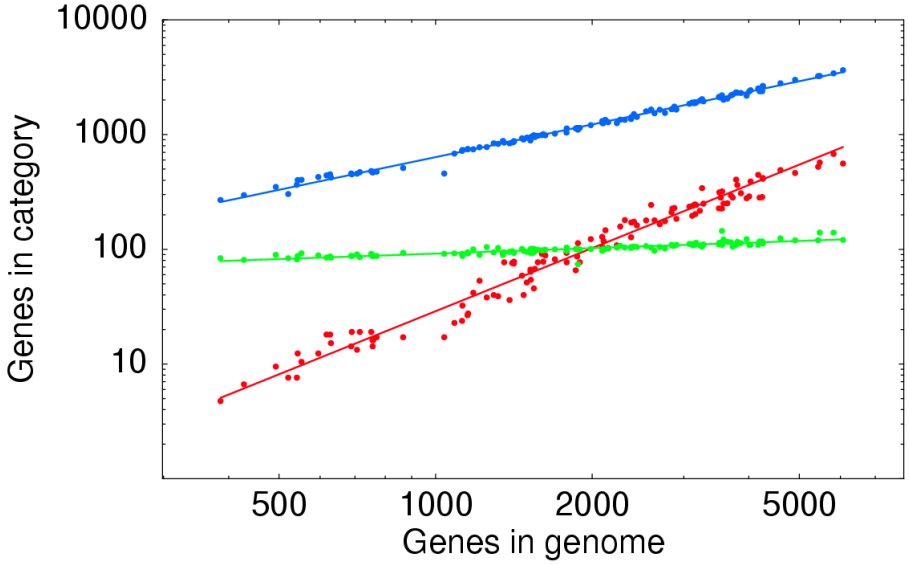




$$\frac{n_R}{n_G} = \frac{\langle regulatory\ inputs\ per\ gene \rangle}{\langle targets\ per\ regulator \rangle}$$

What does it take to generate these plots?





- Genome sequence:
  sequencing and assembly of whole genomes
- Gene identification in whole genomic sequences:
  gene prediction
- Grouping of genes in functional categories:
  functional annotation

Topics that we will address in this course

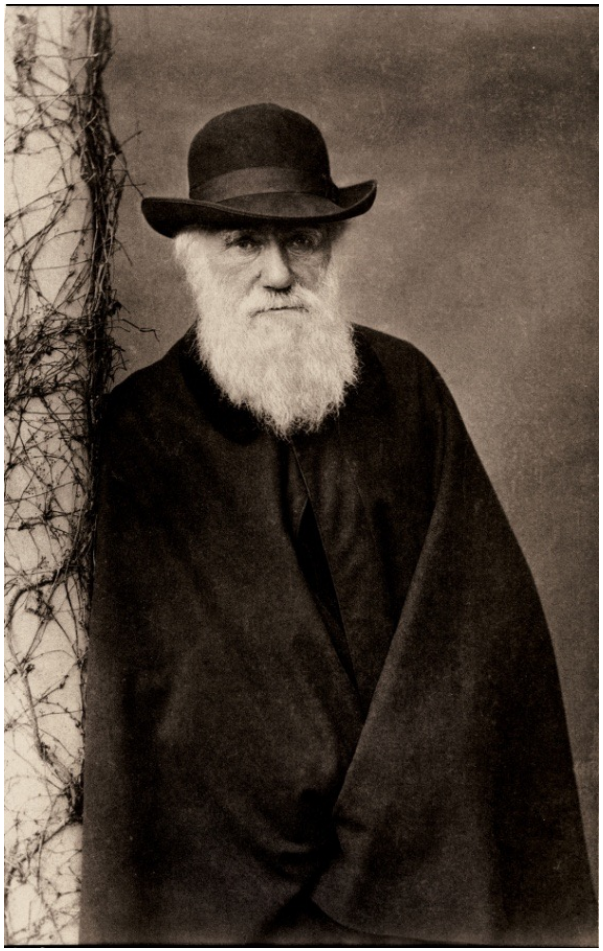
Evolution

An evolutionary process underlies the life we see on Earth today.

What is it evolution?

Evolution is change in the heritable characteristics of biological populations over successive generations. (Wikipedia)

Evolution



Charles Darwin (1809-1882)

If:

1. entities that reproduce
2. with *heritable* variations
3. affecting reproductive success
4. competing for resources

Then: Evolution!

Any system obeying these 4 conditions will evolve.

Example: MEME = replicating (idea, behavior, style) cultural entity (Dawkins).

- An idea replicates from brain to brain.
- People make small mutations to it as they pass it on.
- Variations on an idea can make it more likely to be passed on. For e.g., if somebody makes a joke more funny by a small alteration, the joke is more likely to be passed on.
- Different memes compete for brain space.

1. Replication

Origin of the building blocks of life (amino acids, nucleotides)

Alexander Oparin
(1924)

- A “primordial soup” of organic compounds can form through the action of sunlight in an atmosphere devoid of oxygen.

- They would form ever more complex molecules until droplets (coacervates) would be generated.

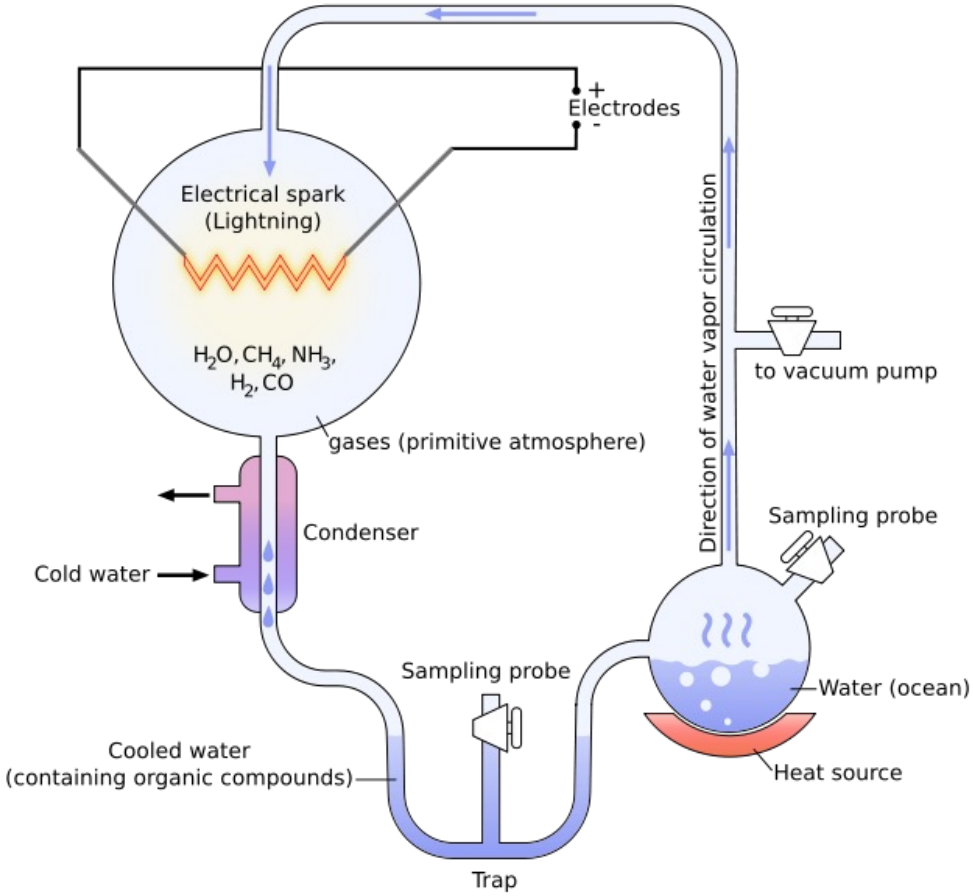
- The droplets could “grow” by fusing with each other and “reproduce” through fission, thereby having a primitive “metabolism”.

Origin of the building blocks of life (amino acids, nucleotides)

Testing the “primordial soup” hypothesis (1953)

Stanley Miller

Harold Urey



Products: amino acids (mixture of L and D forms, most abundant glycine), sugar, lipids. Many experiments followed to show that nucleotides can also be synthesized from inorganic compounds under plausible prebiotic conditions.

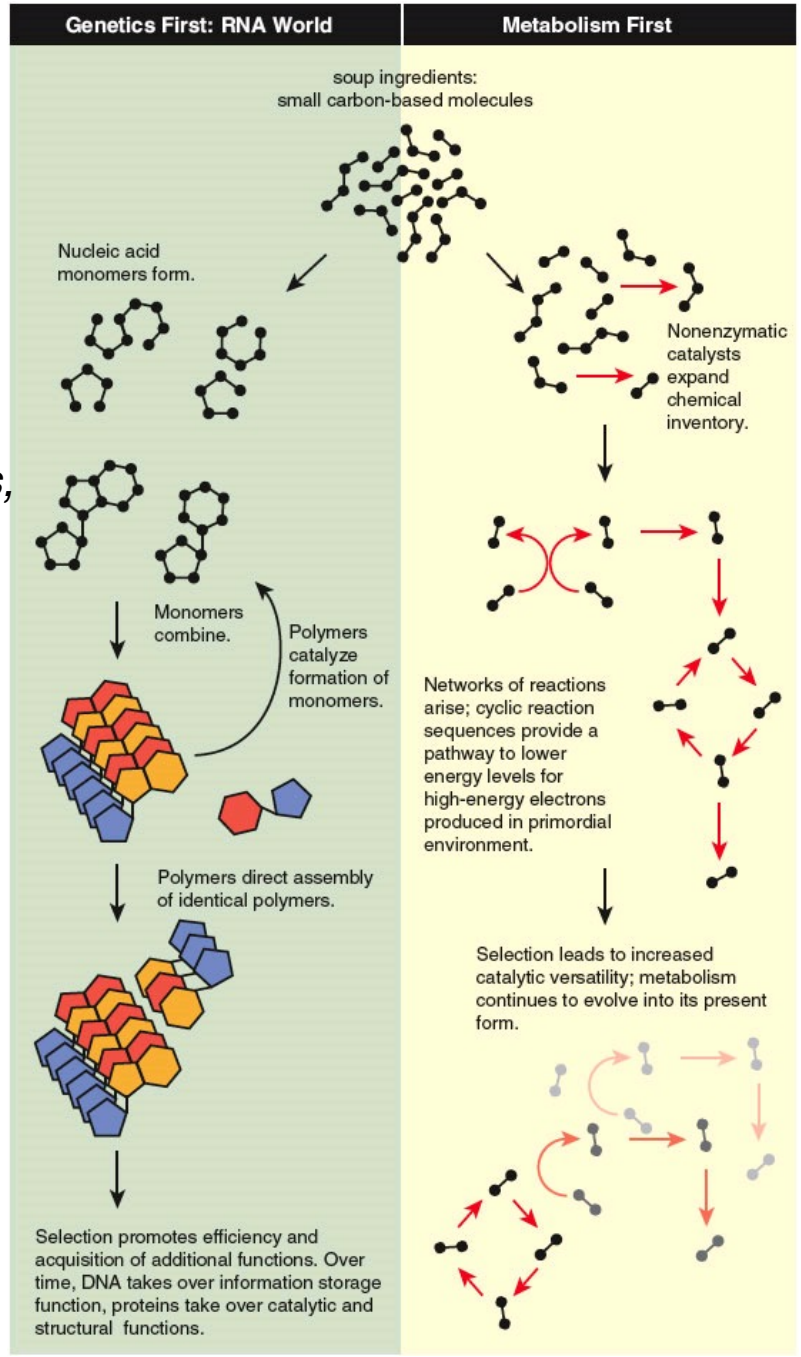
RNA first or metabolism first?

RNA first model.

- From a primordial pool of organic compounds, ribonucleotides are formed.
- Through a chance occurrence, ribonucleotides oligomerize.
- RNAs can act as *enzymes,* including for replicating RNAs.
- Once RNAs are produced that can replicate, evolution starts.

Supporting facts:

- RNAs can both store genetic information and act as enzymes.
- RNAs mediate between DNA and proteins.
- At the catalytic core of the ribosome are rRNAs.



Metabolism first model.

- Many organic compounds available in the primordial soup and many reactions could occur spontaneously (for example at hot vents).
- Eventually an auto-catalytic *cycle* of reactions could be formed.
- Remnants of this cycle would stay at the core of all metabolic networks in organisms (prime candidate: citric acid cycle).
- RNA and genetic information were added later.
- ATP and GTP are universal mediators of energy in all cells.

From:
James Trefil, Harold Morowitz, Eric Smith
American Scientist (2009)

RNA first or metabolism first?

Some issues with the RNA world hypothesis

- cytosine is insufficiently stable at “prebiotic conditions” ($t_{1/2}$ 19 days at 100°C, 17’000 years at 0°C)
- ribose is also unstable under such conditions (73 min at pH 7.0 and 100°C and 44 years at pH 7.0 and 0°C)

Potential solutions

- peptide nucleic acid (PNA), threose nucleic acid (TNA), glycol nucleic acid (GNA)

Philos Trans R Soc Lond B Biol Sci. 2011 Oct 27; 366(1580): 2902–2909. PMCID: PMC3158920
doi: 10.1098/rstb.2011.0139

The meaning of a minuscule ribozyme

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ABSTRACT Go to:

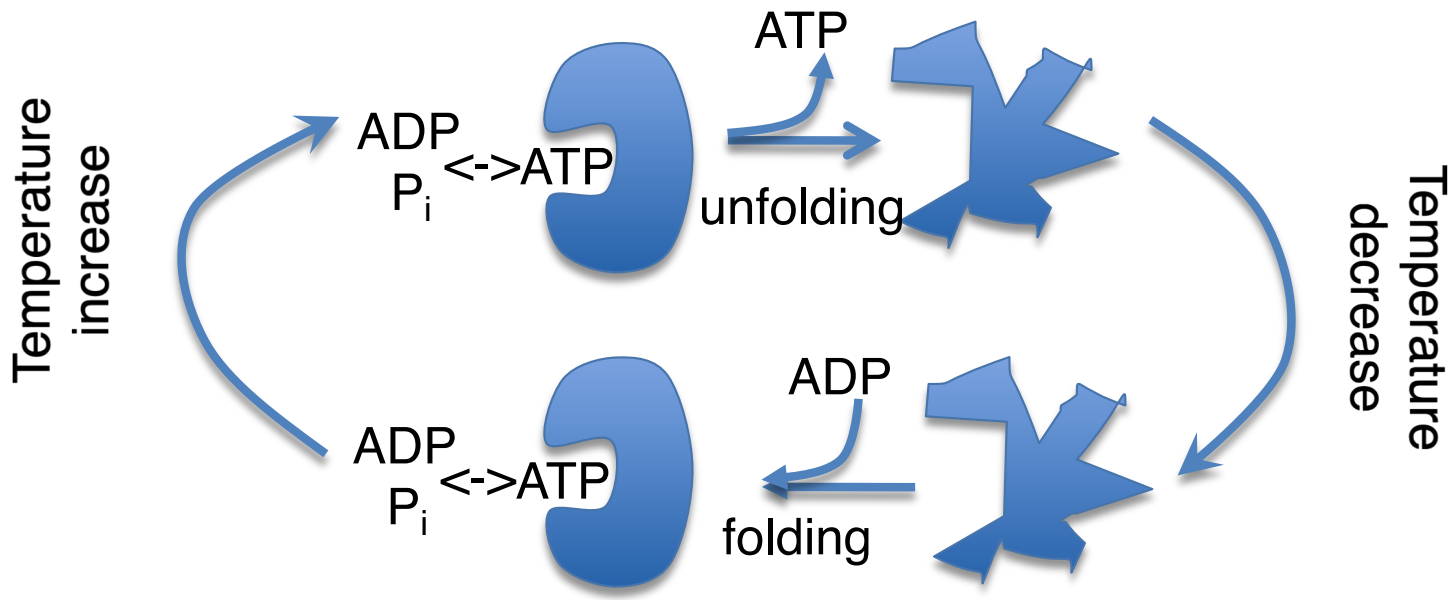
The smallest ribozyme that carries out a complex group transfer is the sequence GUGGC-3′, acting to aminoacylate GCCU-3′ (and host a manifold of further reactions) in the presence of substrate PheAMP. Here, I describe the enzymatic rate, the characterization of about 20 aminoacyl-RNA and peptidyl-RNA products and the pathways of these GUGGC/GCCU reactions. Finally, the topic is evolution, and the potential implications of these data for the advent of translation itself.

Wächtershäuser's 'Pioneer organism'

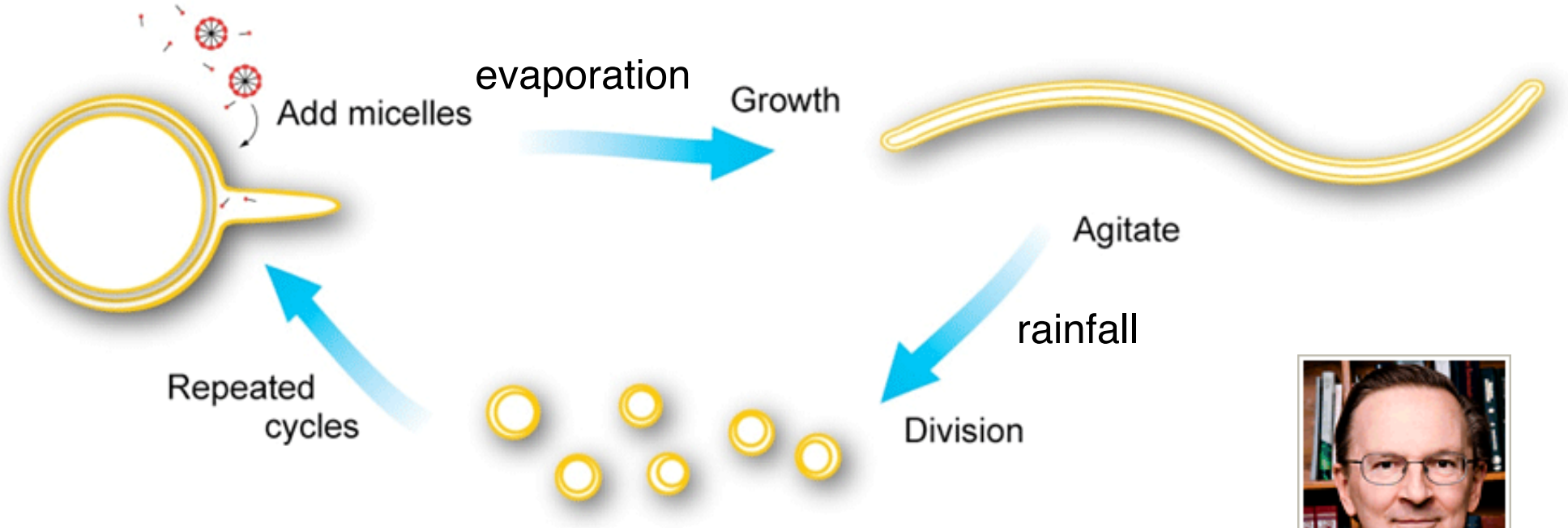
Hypothesis: earliest form of life originated in a volcanic hydrothermal flow at high pressure and high (100 °C) temperature.

Evolution of the first metabolic cycles (https://www.pnas.org/content/87/1/200)

Iron-sulfur world: self-sustained reactions based on the chemistry of thioesters that took place on surfaces (possible connection to the acetyl-CoA synthase of today).
Thermosynthesis world (Anthonie Muller, https://pubmed.ncbi.nlm.nih.gov/16024164/): thermal cycling, which could have occurred as the protocell was suspended for e.g. in a hot spring, would have provided the energy for condensation of substrates bound to the "First protein" (possible connection to ATP synthase of today).



Origin of replication in nature: Splitting vesicles



Jack Szostak
2009 Nobel Prize
Physiology & Medicine

- Starting from a lipid vesicle, addition of micelles leads to spontaneous growth of the vesicle.

- Currents in the solution can easily lead the grown filament to break into pieces.

- This leads effectively to replication of the vesicle.

http://genetics.mgh.harvard.edu/szostakweb/

Replication

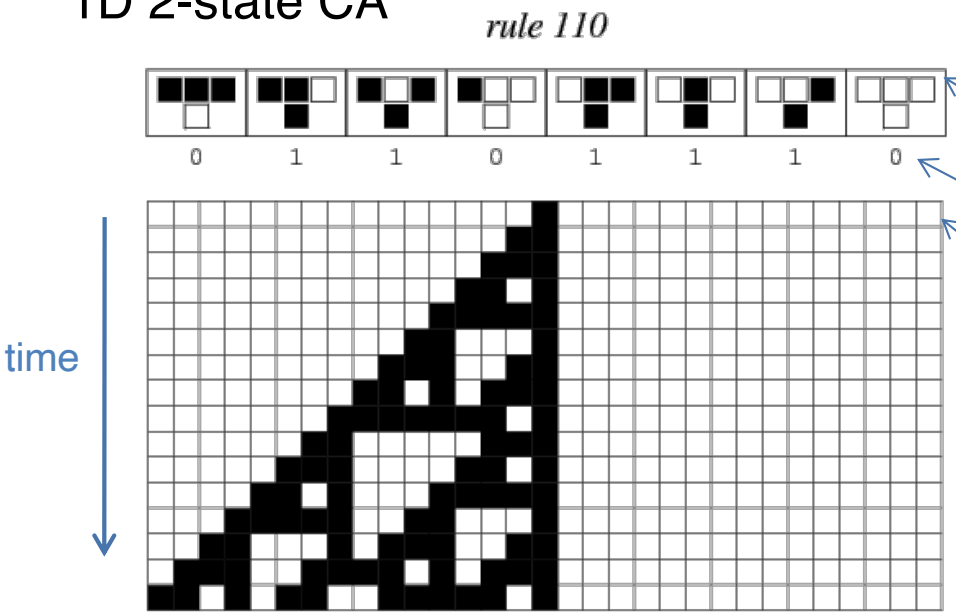
• One of the key features thought to distinguish `living' things from `dead' things.
• Not so long ago, it was unclear to many whether it would be possible to devise artificial objects that *replicate themselves*.
• The mathematician John von Neumann decided to create an abstract mathematical 'world' with simple rules to show how replication can be implemented.

John von Neumann
1903-1957

Cellular Automata

• A grid of cells (1-, 2-, or 3- dimensional).
• Each cell can be in one of *n* states.
• The state of a cell at the next time step depends on its own state and that of its direct neighbors.

1D 2-state CA



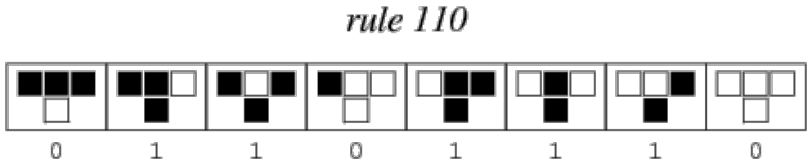
Cell plus its neighbors can be in 8 different states.

The rule specifies the middle cell's state at the next time point.

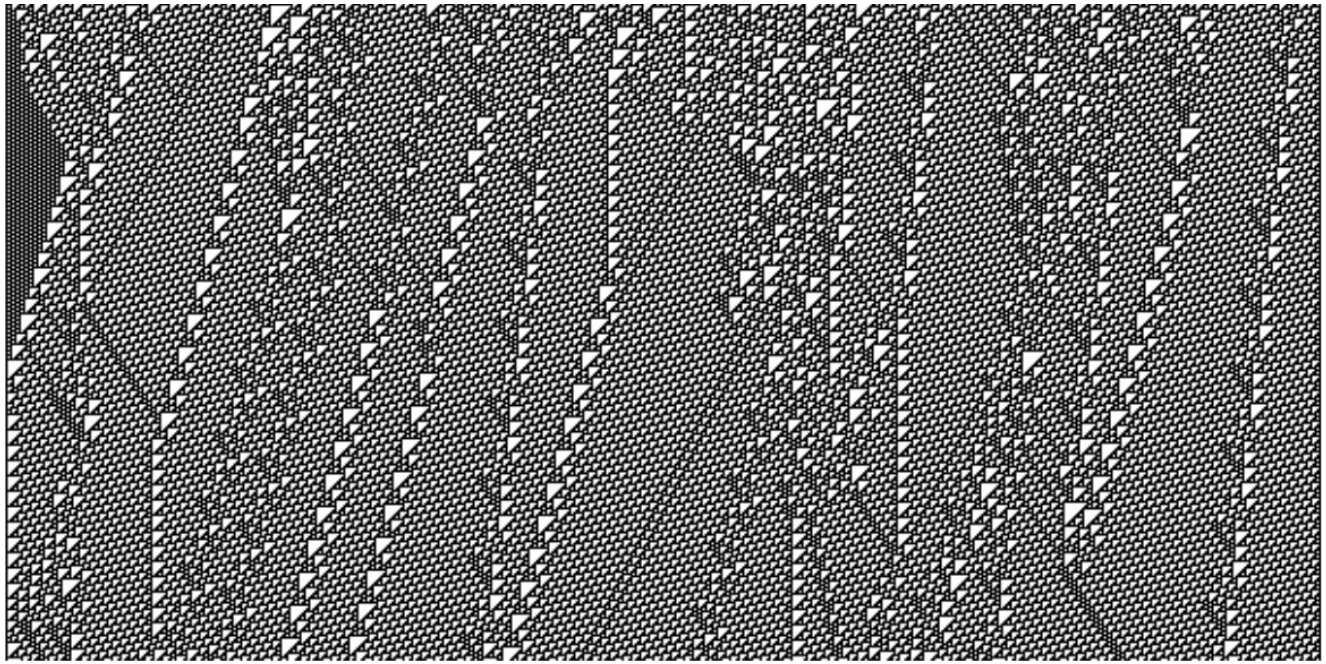
Start from a single cell 'on'.

A pattern will develop over time in this 'world'.

Elementary CA rule 110



Behavior of rule 110 starting from random initial conditions.

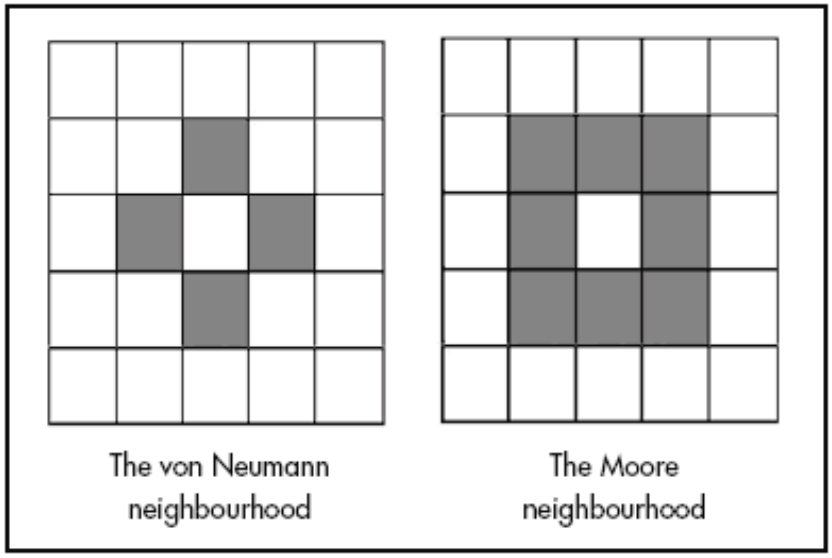


Shows that very complex dynamics can happen even in a world with such simple rules.

Side note:
Around the year 2000, Matthew Cook, working as an assistant to Stephen Wolfram, proved that rule 110 is 'Turing complete", i.e. it can implement *any computation* that any computer can do.
Universality in Elementary Cellular Automata *Complex Systems 15*: 1-40 (2004).

See also: S. Wolfram: A New Kind of Science (2002)

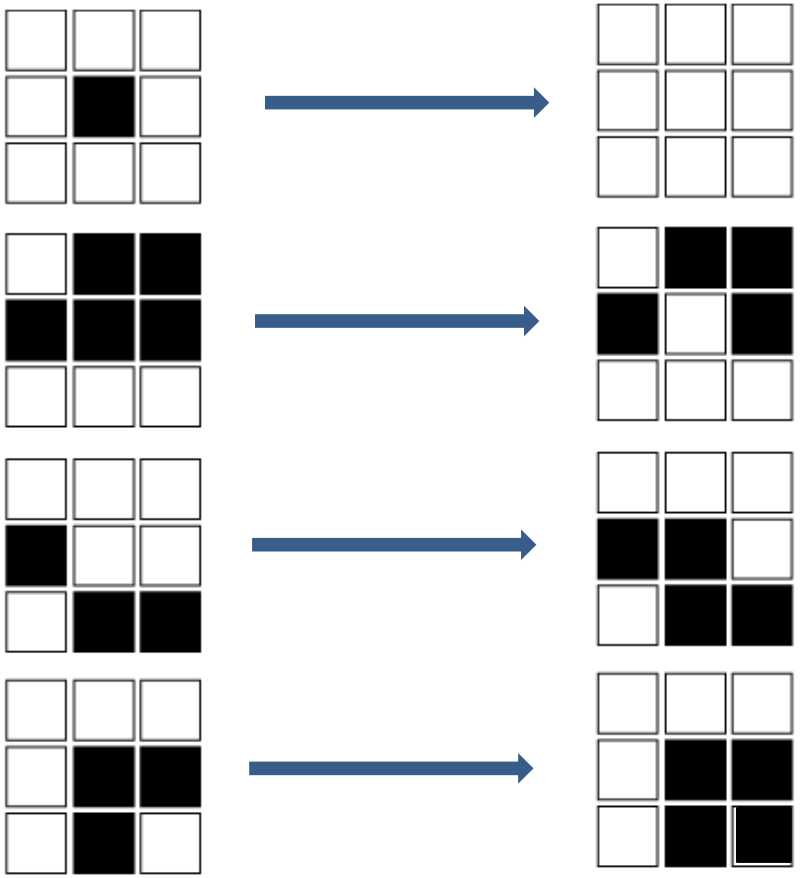
2D Cellular Automata



- The state of each cell at the next time-point is again a function of its state and that of its neighbors.
- Von Neumann used a neighborhood with 4 orthogonal neighbors.
- Many CAs use instead the Moore neighborhood with 9 neighbors.

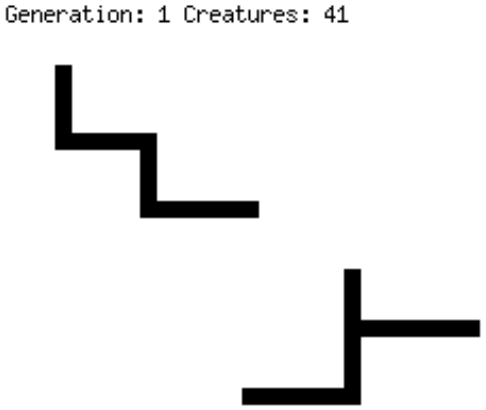
Example:
John Conway's Game of Life (1970)

- A cell that is 'on' will stay on of 2 or 3 of its neighbors are on.
- A cell that is 'off' will come 'alive' when precisely 3 of is neighbors are on.



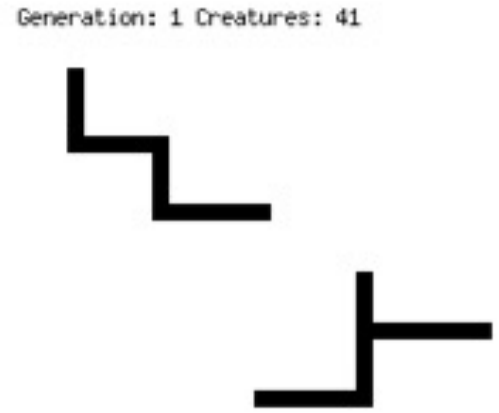
Conway’s Game of Life

Simple example:



Conway’s Game of Life

Simple example:



A ‘glider gun’. A pattern that spits out moving objects:

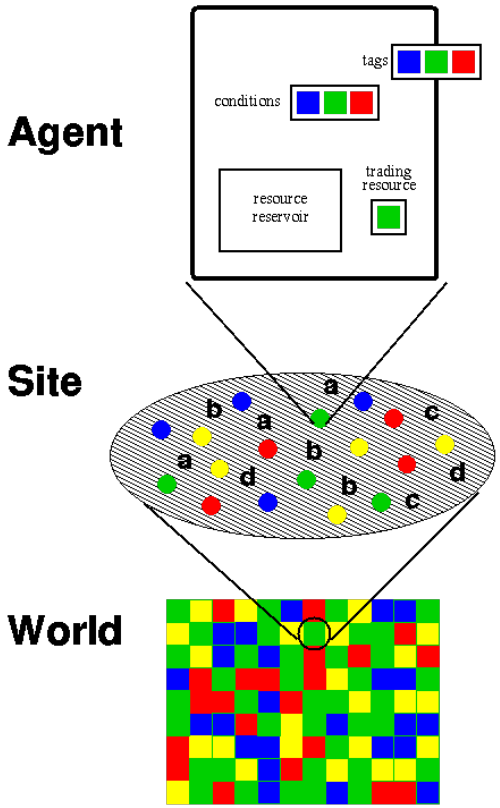
Simulating evolution in a computer with CAs

Echo (Holland, Forrest, Jones, Hraber, et al.)

• simulation tool developed to investigate mechanisms that regulate diversity and information-processing in systems comprised of many interacting adaptive agents.

• Echo agents interact via combat, trade and mating and individual genotypes encode rules for interactions.

• populations of these genomes evolve interaction networks that regulate the flow of resources.



- Reemerging in the study of intra-patient cancer evolution
- Bioinspired computing: genetic algorithms as a problem solving approach

2. Heritable variation

Fuel of evolution

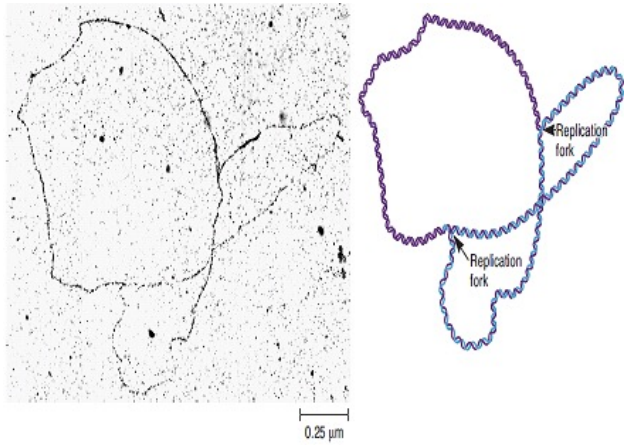
Genetic variation

chegg.com

Where do mutations come from?

The DNA can get damaged.

DNA replication is error-prone.



(b) Autoradiograph of an *E. coli* chromosome in the act of replication

• Replication and repair are done by tiny molecular machines

• Which are subjected to thermal 'noise', other molecules bumping in to them, polymers flopping around, twisting, turning, shaking, etc.

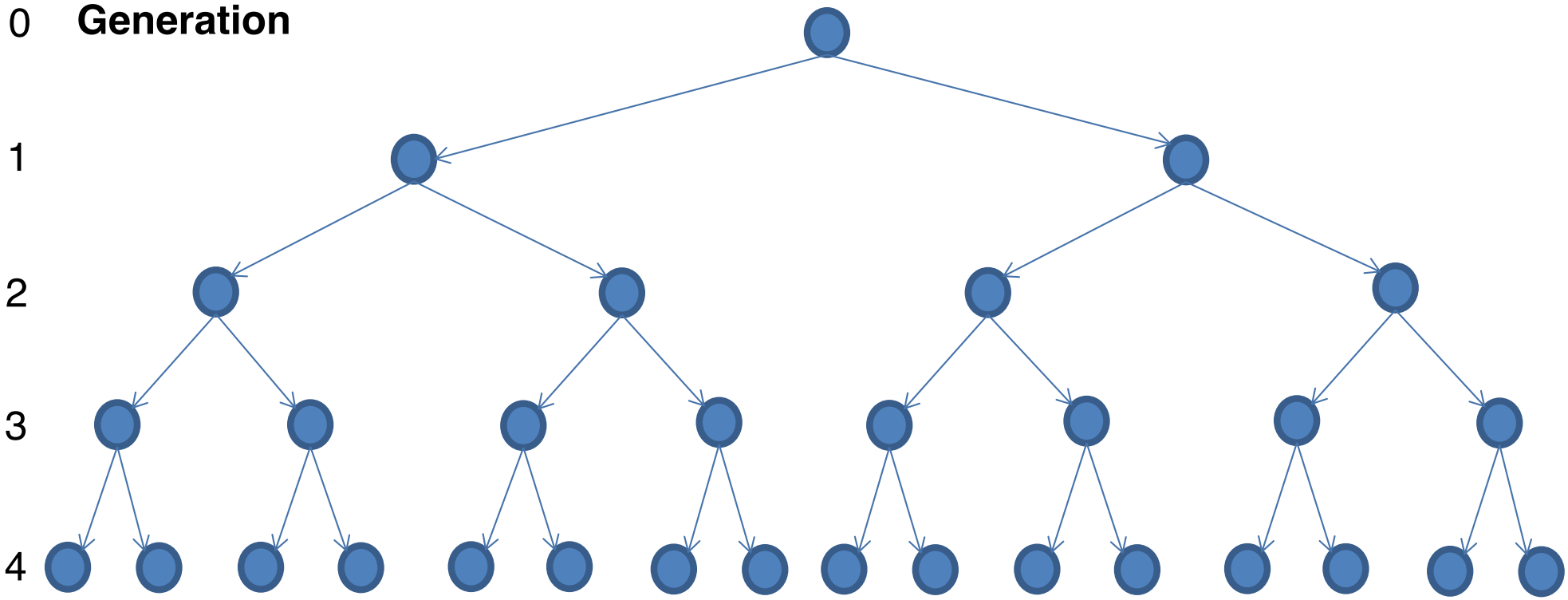
• Mistakes happen

• It is almost impossible to predict where what error will occur. Therefore we describe these *mutation* events as *random*

• This does not mean that mutations don't have some kind of bias (to keep in mind: mutational hot spots)

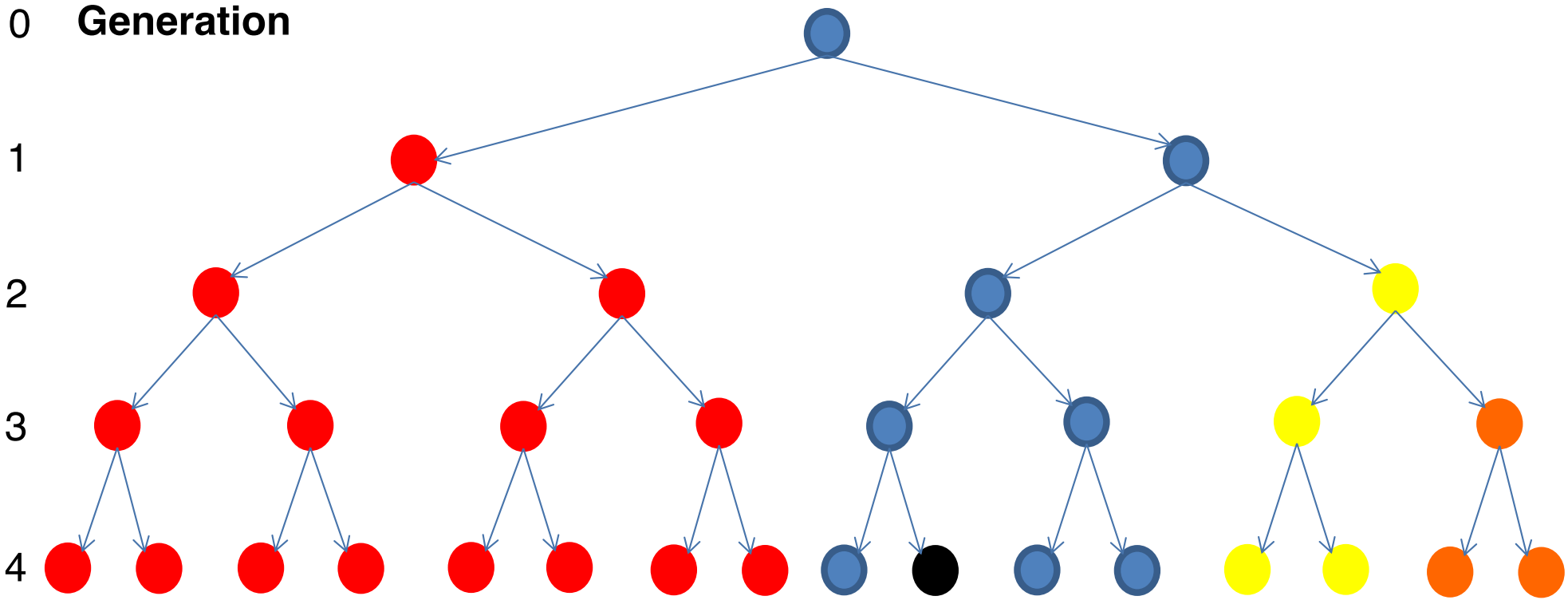
Simplest family relationships: Trees

Let's look at an idealized dynamics of a bacterial cell culture.



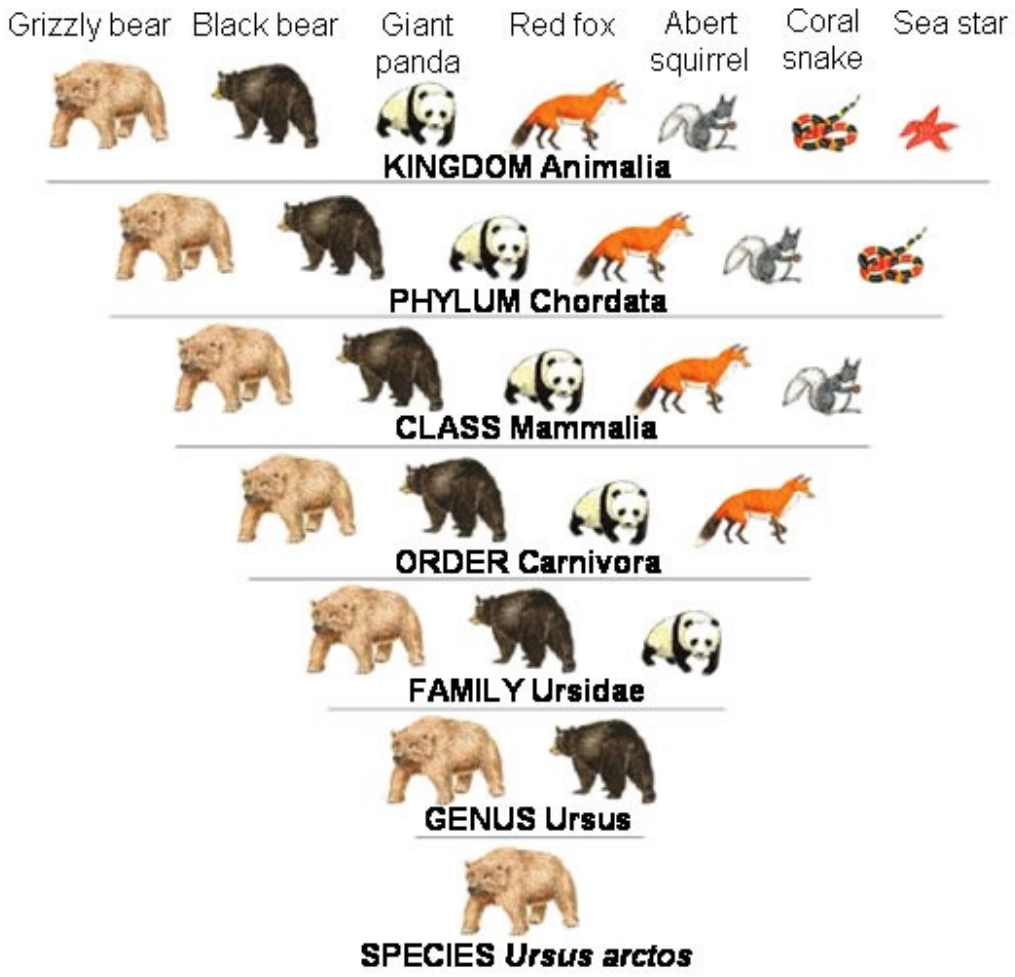
- Each generation the number of individuals doubles
- If we draw arrows from the `parent' individual to the `offspring' we obtain a *tree* structure

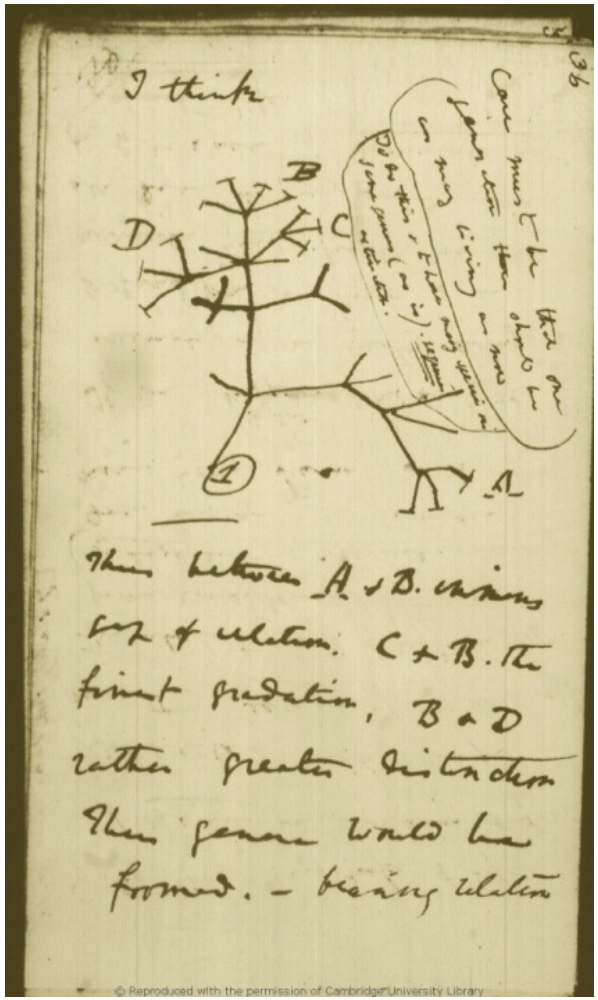
Heritable variation



- Each generation the number of individuals doubles
- If we draw arrows from the `parent' individual to the `offspring' we obtain a *tree* structure
- Heritable `mutations' naturally induce *hierarchical* similarities, reflecting *family relationships*

Consistent with species classifications

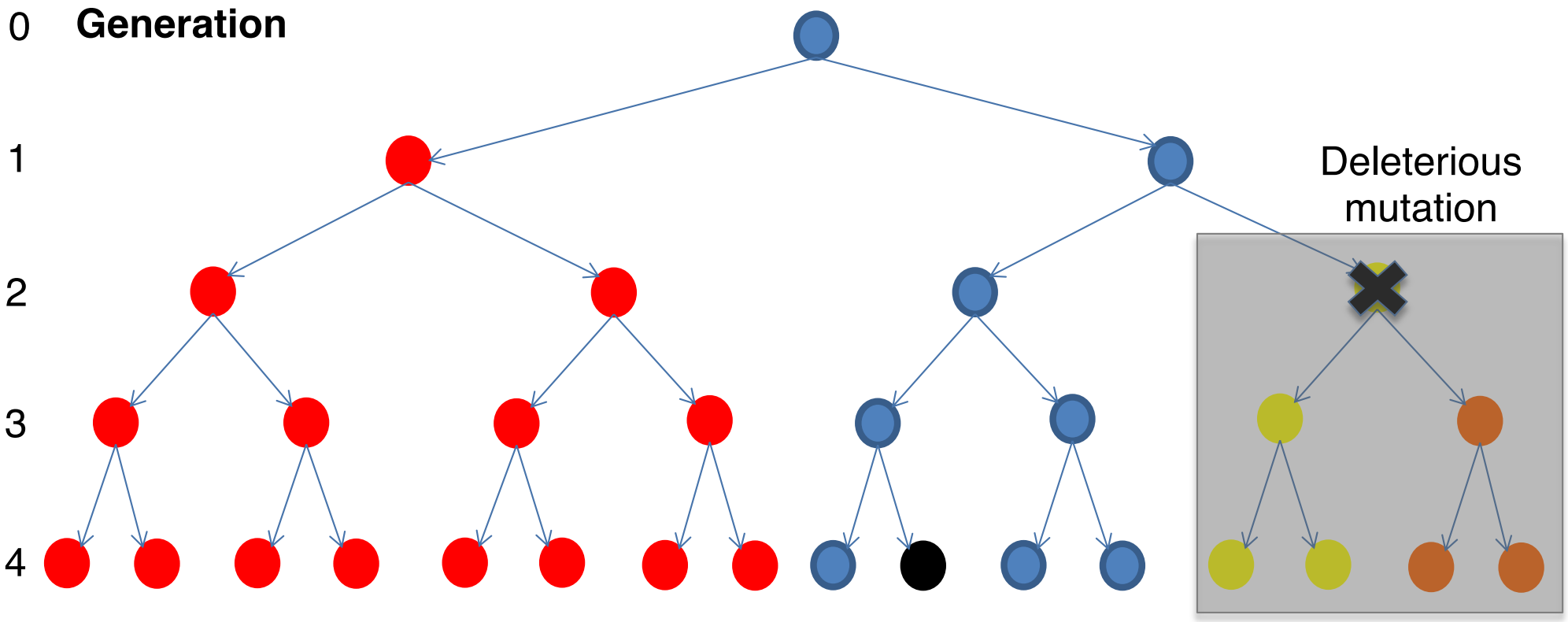




But very different meaning

3. Reproductive success

Reproductive success



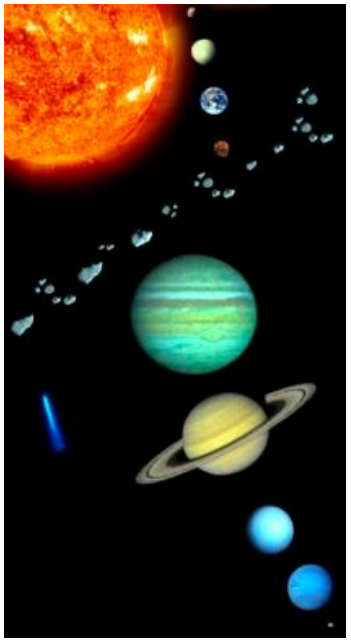
In our initial system
each bacterium divided into two
the time between divisions was identical

More realistically, mutations affect
whether and how fast bacteria are dividing

The structure of the resulting trees will be very different

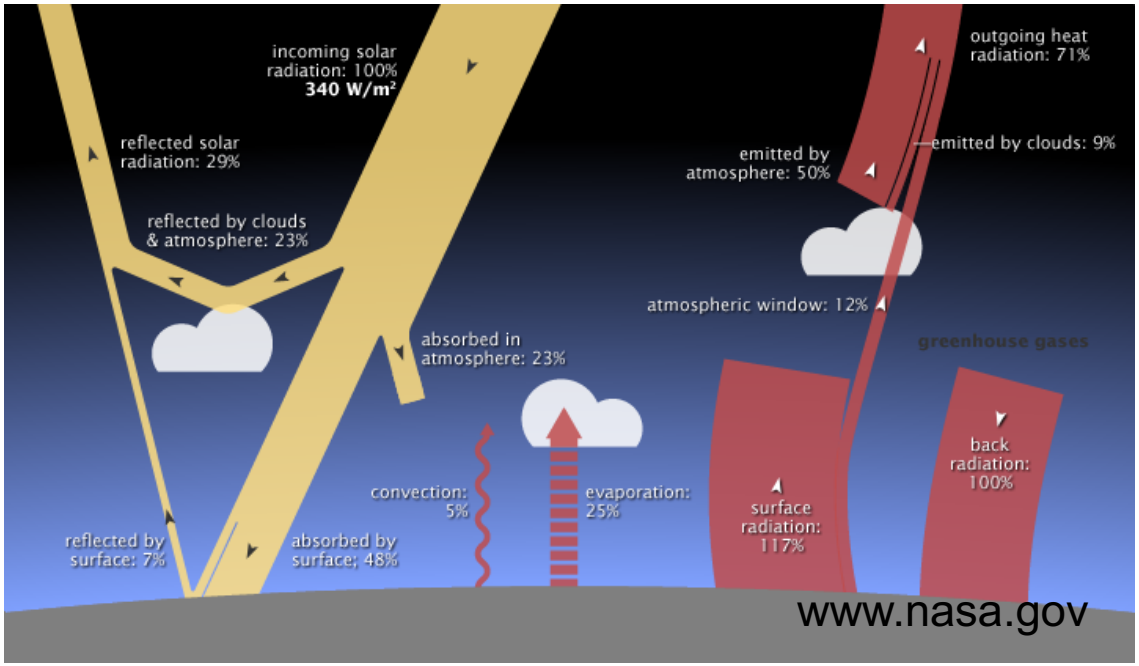
4. Competition for resources

Competition for resources. Energy flows



Physics tells us *energy is a conserved quantity*.

To replicate, a structure needs energy from somewhere.



- Essentially all energy input to the planets comes from the sun.
- Where does this energy go?

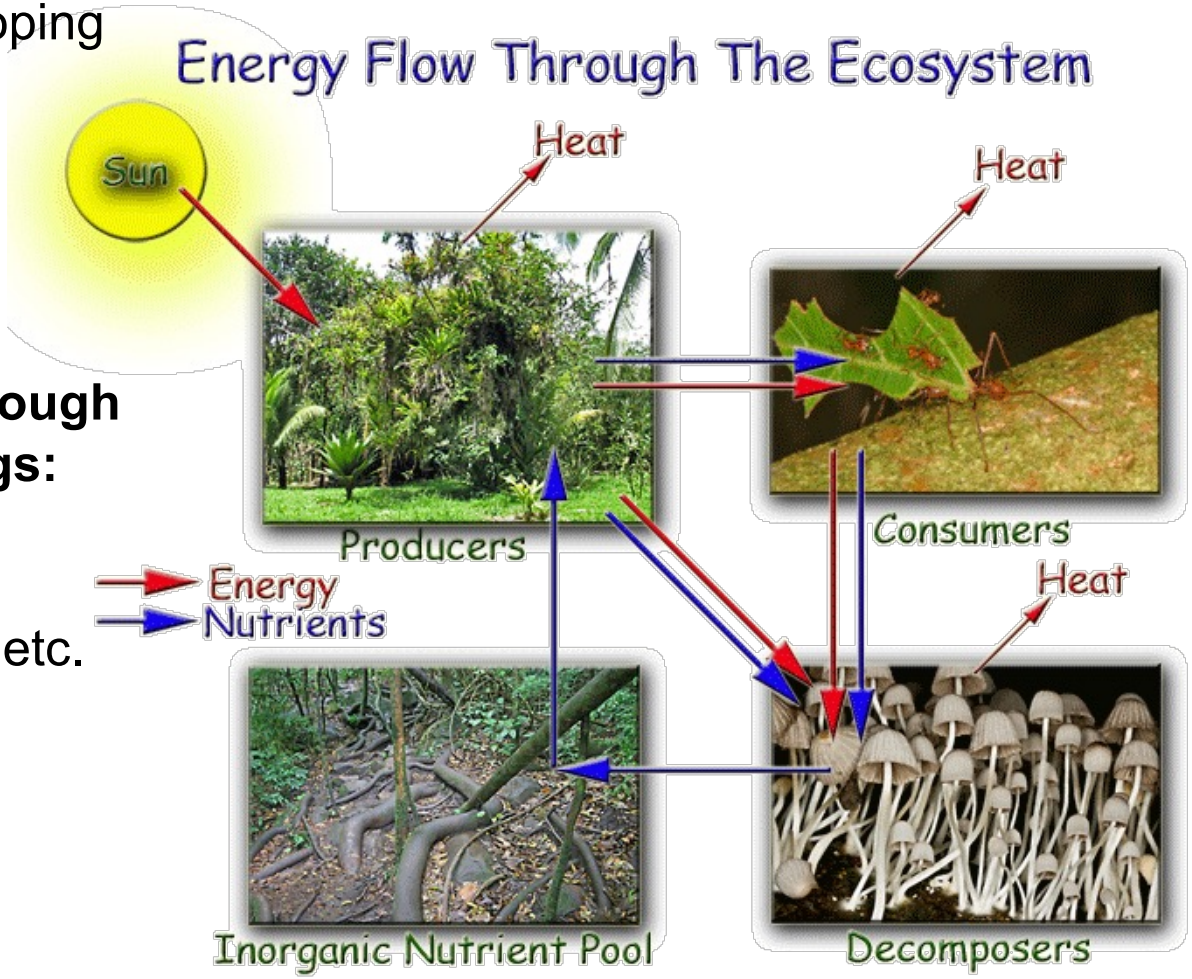
The energy will *dissipate* through the system.

- The molecules in the atmosphere and on the surface of the planet will *heat up*.
- Differences in heat can cause *currents* of gases and liquids.
- These currents cause erosion of materials, and drag small particles along.
- Provided enough heat is present *chemical reactions* will take place.
- This can *alter* the state of the planetary system.
- Many of these events occur in cycles, hot/cold, light/dark, etc.
- Thermodynamics: Energy will go wherever it can.

Energy flows. Competition for resources

One way to think of evolution:

• Evolution is a very slowly developing response of the physical system 'earth' to energy from the sun. It constantly finds more elaborate 'paths' for dissipating energy.



Energy dissipates further through the ecosystem of living beings:

• Plants use sunlight directly.
• Ants eat leafs.
• Fungi decompose dead ants, etc.

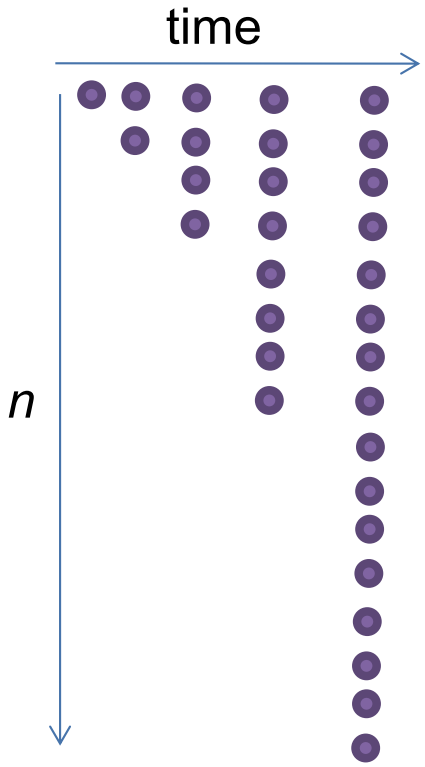
Other conserved quantities:

• Water (more or less recycled).
• The total number of atoms of different kinds, i.e. important atoms like carbon, oxygen, nitrogen, and phosphate cannot be replicated, they have to be taken from somewhere.

http://www.marietta.edu/~biol/biomes/ecosystems.htm

Competition

The number of replicating entities grows *exponentially* in time



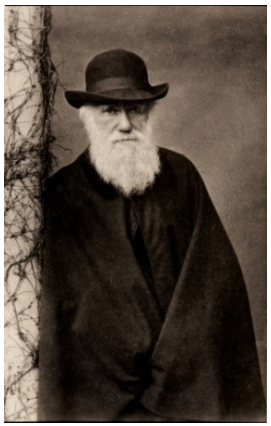
$n(t) = 2^{t/\tau}$ with τ the replication time.

• The amount of energy and basic components needed are thus also growing exponentially.

• Very quickly, there will not be enough resources (basic compounds and energy) to keep doubling.

• To keep growing in number, there are two options for a replicator:

1. Find an new source of energy and compounds, i.e. find a new *niche* to live in.
2. Get *better* at getting the resources than its neighbor, i.e. *outcompete* them.



Crucial ideas:
Limited resources imply that there will be a competition between replicators and this will lead to evolution of 'fitter' individuals.
When replicators find ways to use different resources this will lead to co-existence of replicators in different *niches*.