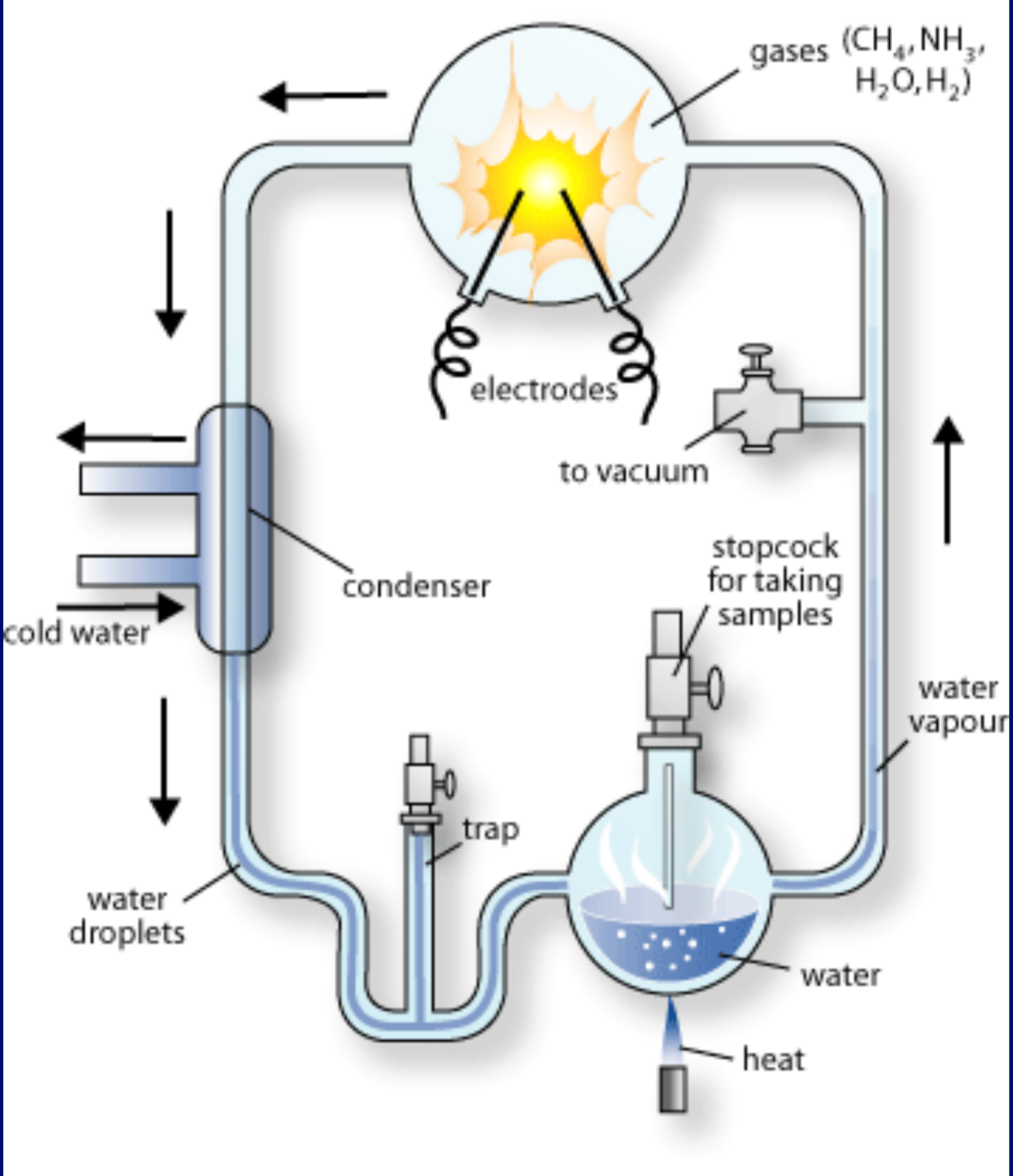
Origin of Life: I
Monomers to Polymers

Synthesis of Monomers

- Life appears early on Earth (3-4 Gyr ago)
- Conditions:
  - Liquid water
    - Earth in HZ
  - Reducing or Neutral atmosphere
    - NH_3, CH_4, H_2O, H_2 or CO_2, N_2, H_2O (no O_2)
  - Energy sources
    - Ultraviolet Light (No Ozone)
    - Lightning
    - Geothermal (Lava, Hot Springs, Vents, …)

Miller-Urey Experiment: 1953



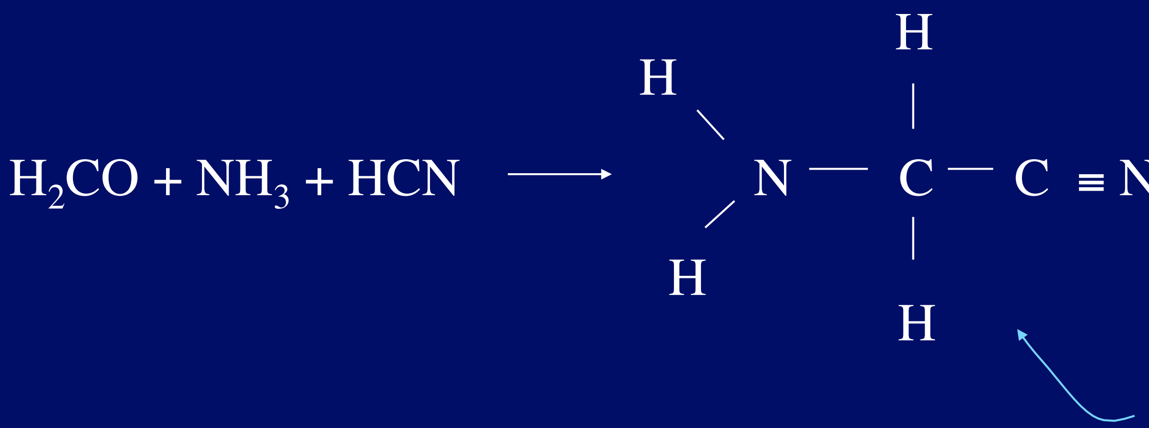
Products of Miller-Urey

COMPOUND	Relative Yield
Glycine	270
Sarcosine	21
Alanine	145
N-methylalanine	4
Beta-alanine	64
Alpha-amino-n-butyric acid	21
Alpha-aminoisobutyric acid	0.4
Aspartic acid	2
Glutamic acid	2
Iminodiacetic acid	66
Iminoacetic-propionic acid	6
Lactic acid	133
Formic acid	1000
Acetic acid	64
Propionic acid	56
Alpha-hydroxybutyric acid	21
Succinic acid	17
Urea	8
N-methyl urea	6

How did Amino Acids form in Miller-Urey Experiment?

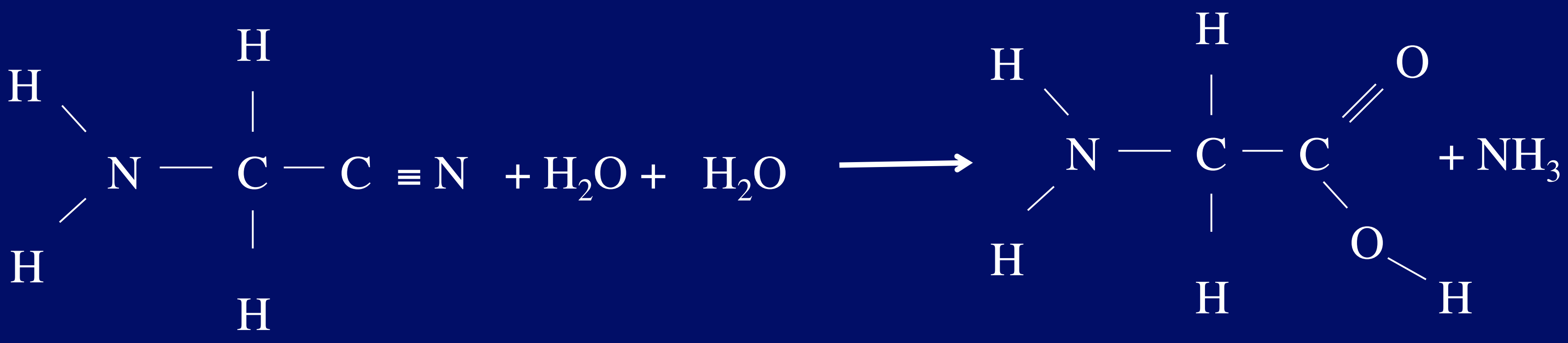
Strecker Synthesis e.g. Glycine Synthesis

$$\mathrm{CH_4, H_2, NH_3} + \text{Energy} \longrightarrow \underbrace{\mathrm{H_2CO, HCN, HC_3N,}\ \text{Urea}\ (\mathrm{H_2\,NCONH_2})}_{\text{Reactive}}$$



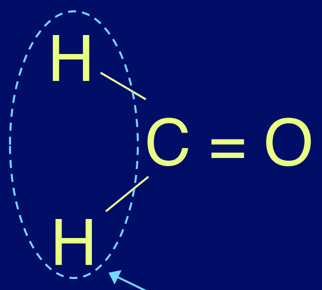
$$\mathrm{H_2CO + NH_3 + HCN} \longrightarrow \mathrm{H_2N{-}CH_2{-}C{\equiv}N + H_2O}$$

Aminoacetonitrile



glycine

H_2CO



form Aldehyde

Replace with more complex group
Get other aldehydes ↓
They can form more complex amino acids

Building Blocks of Nucleic Acids

Not formed in Miller-Urey, but some intermediates were

1. Ribose Sugar:

   $5\ \ H_2CO + \text{Heat} \longrightarrow H_{10}C_5O_5$

   [Clay Catalyst]

2. Bases

   a) Purines $5\ HCN \rightarrow H_5C_5N_5$ (Adenine)

   b) Pyrimidines

   $HC_3N + \text{Urea} \longrightarrow H_5C_4N_3O$ (Cytosine)

   Cyanoacetaldehyde + Urea → Uracil

3. Phosphate

Rock Erosion

Origin of building blocks of nucleic acids is less understood than amino acids

Some recent progress: simulate a meteorite impact onto a mixture of clay and formamide ($HCONH_2$); all four bases produced

Problems with Miller-Urey

Atmosphere was N_2, CO_2, H_2O

NH_3, CH_4 would react to make N_2, CO_2

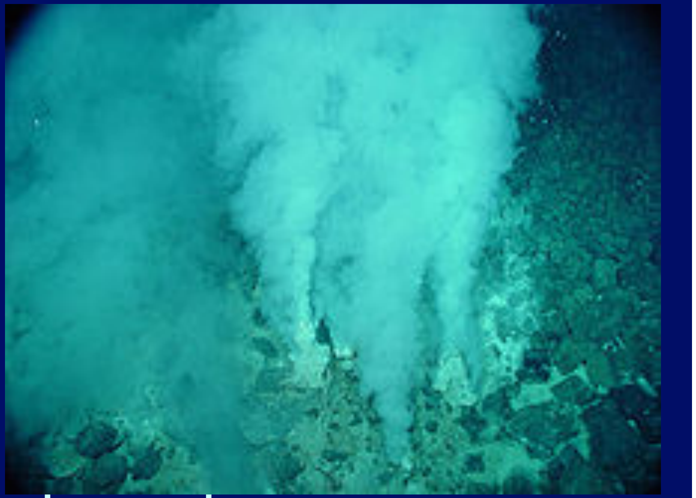
Try N_2, CO_2, H_2O in Miller-Urey simulation

Only get trace amounts of glycine

Need CH_4 to get more complex amino acids

Need $H_2/CO_2 > 2$ to get much of any amino acid

Alternative Sites



Locally reducing environments

1. Ocean vents

   Sources of CH_4 and H_2S

   Current Vents have ecosystems based on energy from chemicals - not photosynthesis

   $H_2S \longrightarrow$ Bacteria $\rightarrow$ Clams, Tube Worms

   Pre-biotic amino acid synthesis?

   Further evolution to life? Ancient anaerobic microbes use similar chemical pathways to conditions found in alkaline vents, such as Lost City

Alternative Delivery

2. Molecular clouds - strongly reducing, contain many molecules used in Miller-Urey (H_2, NH_3, H_2O, CH_4) and intermediates (HCN, H_2CO, HC_3N) and aminoacetonitrile (glycine precursor)

Problem: These would not have survived in part of disk where Earth formed

But interstellar ices can get incorporated into comets and some asteroids.

Evidence from similar molecules

(e.g. C_2H_2, CH_4, HNC, …)

Cratering record on moon, …

⇒ heavy bombardment early in history

Comets, asteroids, and their debris could have brought large amounts of “organic” matter to Earth

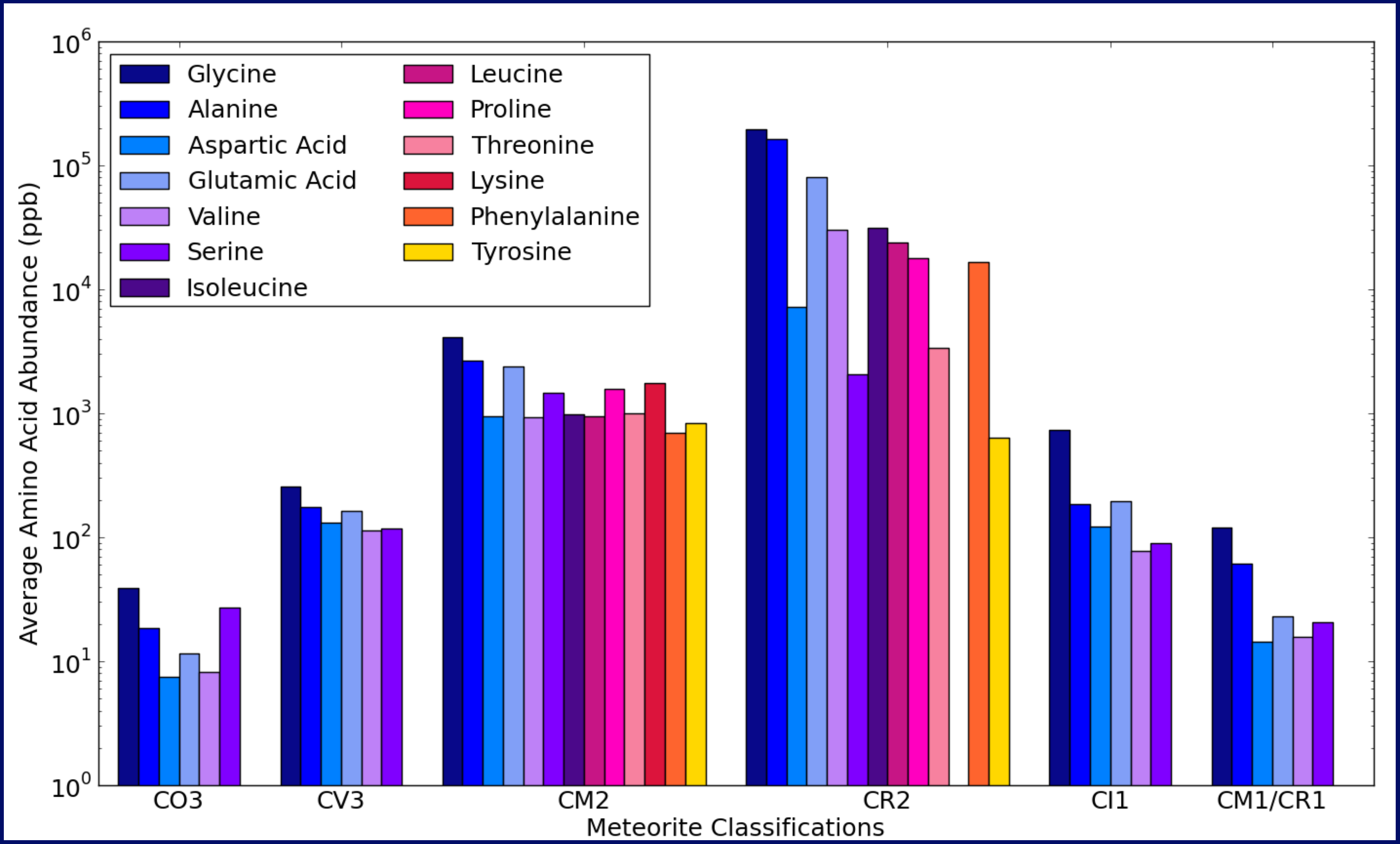
(and probably the oceans)

Some evidence for non-biological amino acids in layer deposited after asteroid impact 65 million years ago

Amino Acids in Meteorites

- Amino acids are found in some classes of meteorites (carbon-rich ones)
- Recent analysis of some carbon-rich meteorites found in Antarctica
  - Richest source of amino acids so far
  - Up to 250 parts per million
  - Very clearly extraterrestrial (not contamination)
    - Type of amino acids
    - ^{13}C is enhanced (opposite of what life does)

Amino Acids in Meteorites



Cobb and Pudritz 2014

Sources of Organic Molecules

Quantitative comparison by Chyba & Sagan, Nature 1992, Vol. 355, p. 125

Currently, Earth accretes ~ 3.2×10^6 kg y^{-1} from interplanetary dust particles (IDP)

~ 10% organic carbon ⇒ 3.2×10^5 kg y^{-1}

~ 10^3 kg y^{-1} comets

~ 10 kg y^{-1} meteorites

~ $10^3 \times$ more at 4.5×10^9 yr ago (?)

(cratering record)

UV + reducing atmosphere 2×10^{11} kg y^{-1}

But if $H_2/CO \lesssim 0.1$ IDP's dominant source

So if atmosphere very neutral, IDP's may have been important

Most of mass in IDP's in range of size ~ 100 μm

mass ~ 10^{-5} g

Complex structure - composites of smaller grains, some carbon rich

Enhanced deuterium implies low T

Deuterium enhancement also found in interstellar molecules

May imply connection back to interstellar chemistry

2 kinds (mass ranges) can supply organic matter

1. Interplanetary dust particles ($m \lesssim 10^{-5}$ g)
2. Smaller meteorites ($m \lesssim 10^{8}$ g)

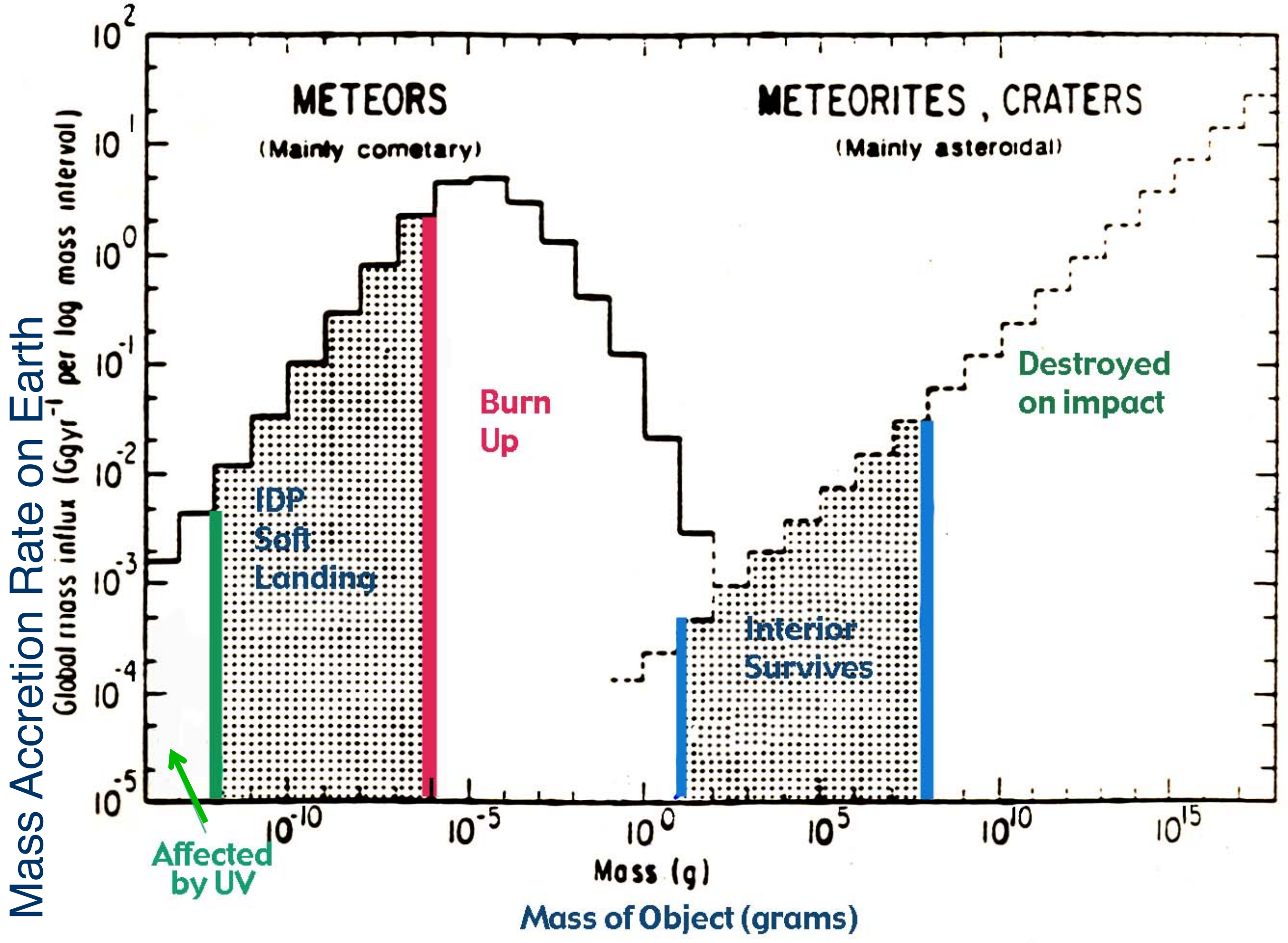


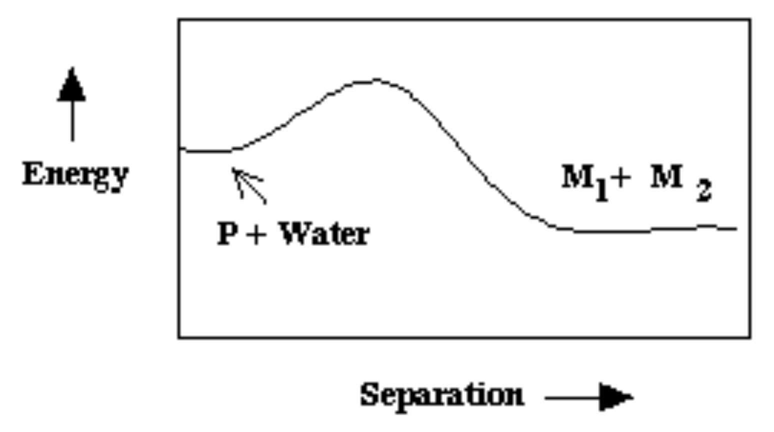
FIG. 1 Infall rate of meteoritic matter on Earth (adapted from ref. 5). Intervals where organic matter can survive passage through atmosphere are shaded. The curve on the right is based on the relation[5] $N = 0.54\, r^{-2.1}$ (N = number of impacts per Myr, r = radius in km), for an assumed density of 3 g cm^{-3}. The corresponding mass accretion rate (Gg yr^{-1}) between r_1 and r_2 is 15.83 $(r_2^{0.9} - r_1^{0.9})$.

E. Anders (1989) Nature, 342, 255

Synthesis of Polymers

$M_1 + M_2 \longrightarrow P + H_2O$

$\longleftarrow$ more likely in liquid H_2O



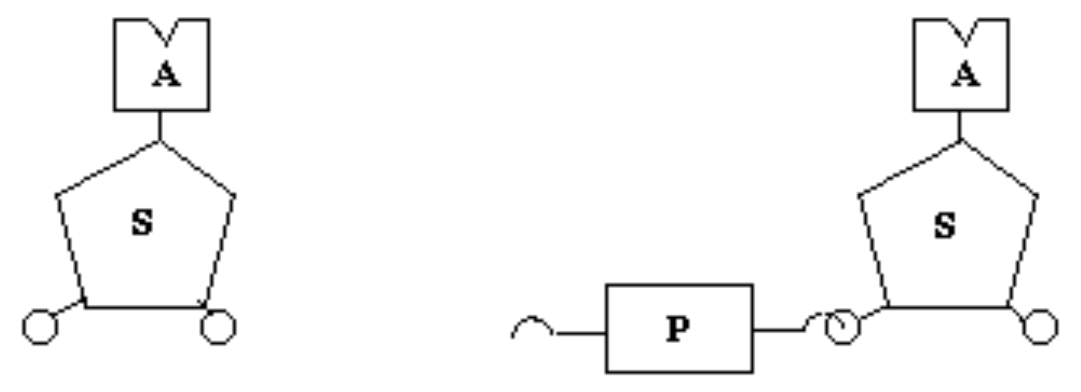
Solutions: Remove H_2O (Drying, Heat)

Sydney Fox $\longrightarrow$ Proteinoids

Energy Releasing Reactions (H_2NCN or HC_3N)

Catalysts: Clays

Problem is worse for Nucleic acids because more complex



nucleoside

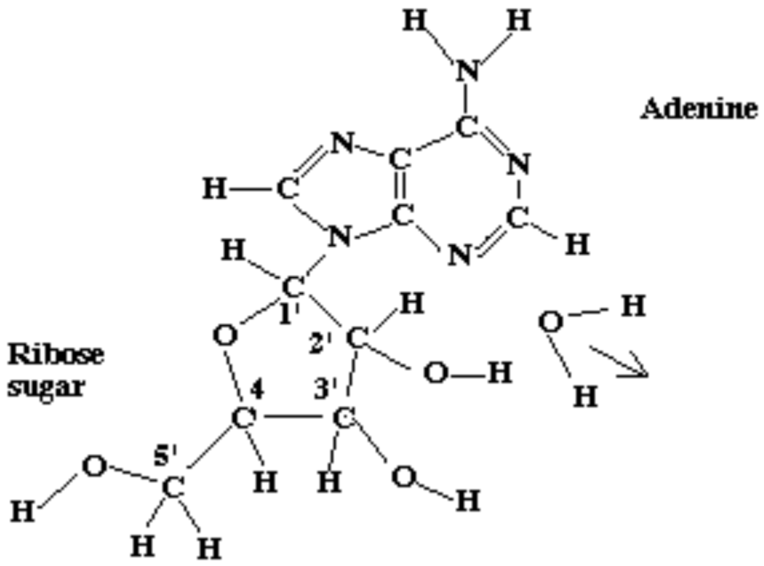
nucleotide

↑

Monomers of nucleic acids

Synthesis of Adenosine

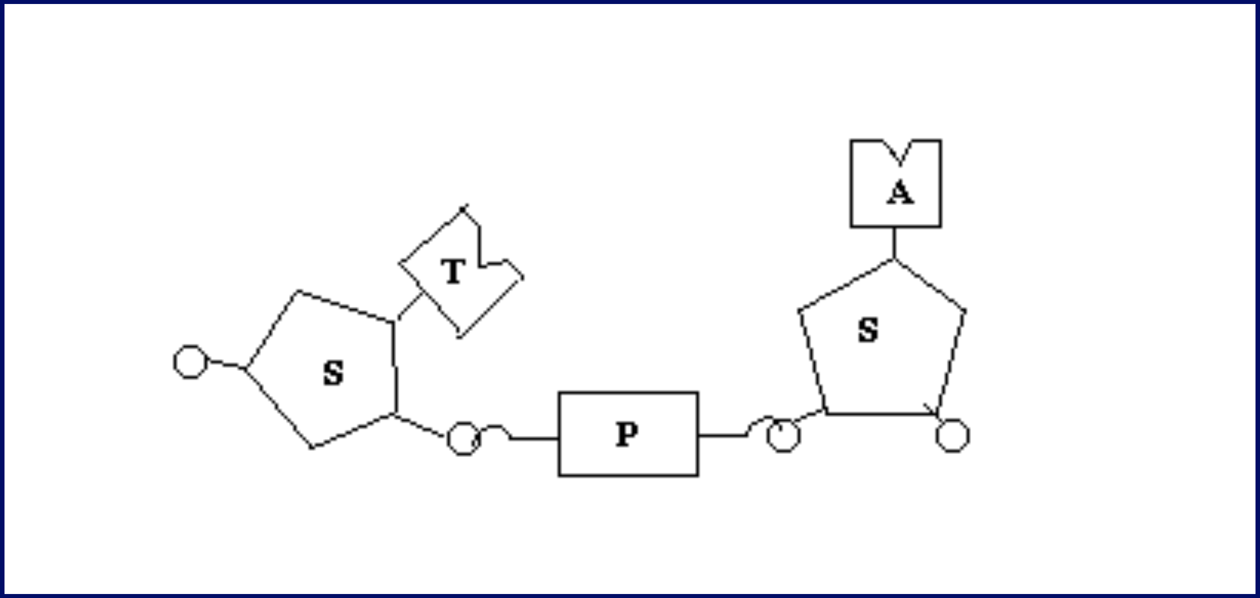
Base on 1’ Carbon (Why?)



Adenine + ribose sugar → adenosine + H_2O

Also phosphates 3’ & 5’ carbons

Otherwise, you are likely to get Misalignment



New Approach

- Progress from a group in England
  - Mix HCN, H_2CO, … and phosphate
  - Energy led to nucleotides without making sugars, bases. Different route.
  - Linkages not all correct
  - But exposure to ultraviolet destroyed incorrect ones.
  - Clay soils can catalyze polymerization into nucleic acids.

The Odds

- We need to get an “interesting” polymer
  - Enzyme
  - Self replicator
- Properties of polymer depend on
  - Order in which monomers combine
- If we combine monomers at random,
  - How likely to get something interesting?

Statistics of an unlikely event

Random reactions in primordial soup?

Unlikely event versus many trials

Probability Primer: Consider tossing 10 coins

Probability of all heads = product of prob.

$$P = \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) \cdots \left(\frac{1}{2}\right)^{10} = \frac{1}{1024}$$

Probability of getting 10 amino acids → protein

Chosen from 20 in a particular <u>order</u>

$$\left(\frac{1}{20}\right)^{10} = \frac{1}{1 \times 10^{13}}$$

Based on discussion by
R. Shapiro

But if you try many times, the chance of success is higher

$$P(r) = \frac{n!}{r!\,(n-r)!}\quad p^{r}\,(1-p)^{n-r}$$

r = # of successes $\quad$ p = prob. of success on each trial

n = # of trials

$n! = n\,(n\text{-}1)\,(n\text{-}2)\,\ldots\,1$

e.g. make $n = \frac{1}{p}$ (flip all 10 coins 1024 times)

$$P(1) = \frac{n!}{1!\,(n-1)!}\left(\frac{1}{n}\right)\left(1-\frac{1}{n}\right)^{n-1} = 0.37$$

Chance of one or more successes = 0.63

For reasonable chance need $n \sim \frac{1}{p}$

How many do we have to get right?

1. How many atoms?

Lipids	$10^2 - 10^3$
Enzymes, RNA	$10^3 - 10^5$
Bacterial DNA	$10^8 - 10^9$
Bacterium	$10^{11} - 10^{12}$
Human Being	$10^{27} - 10^{28}$

If we choose from H,C, N, O (ignore S,P)

probability of right choice 1/4

So for enzyme: $\left(\frac{1}{4}\right)^{10^3} \sim 10^{-600}$

# of trials: R. Shapiro computes

$N = 2.5 \times 10^{51}$ (surely an overestimate)

$n \ll \frac{1}{p}$ for simple enzyme

2. What if we start with amino acids?
   Need $\sim 10^{13}$ trials to get 10 amino acid protein

To get 200 amino acids in right order

$$\left(\frac{1}{20}\right)^{200} = 10^{-260}$$ Hopeless!

Need something besides random combinations

Selection (Natural?)

Improving the Odds

Many proteins composed of interchangeable segments (Domains)

10 to 250 amino acids

One domain found in ~ 70 different proteins

Intermediate building blocks?

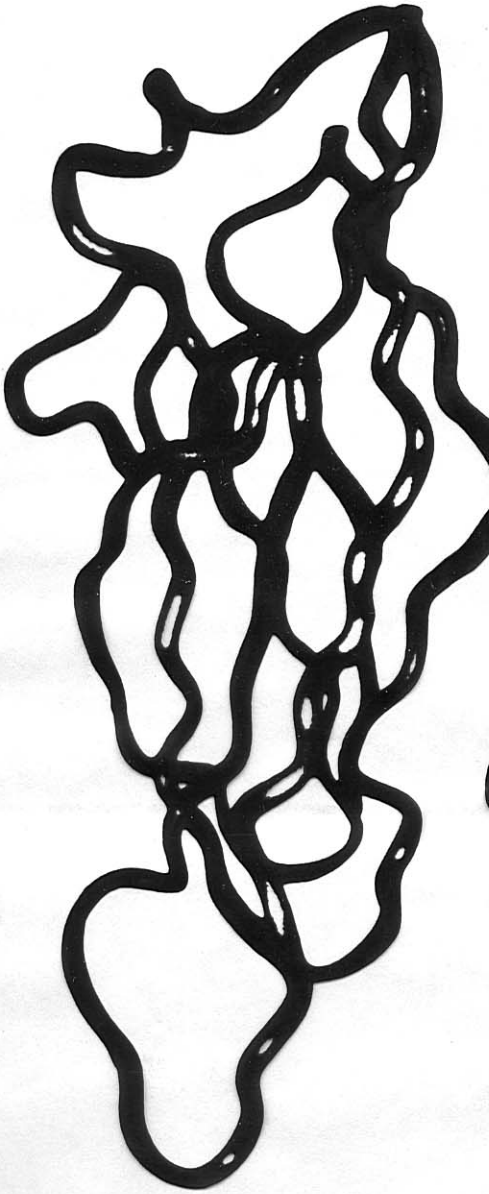
If so, may only need to get enough amino acids in right order for a domain e.g. 18 amino acid domain

$$P = \left(\frac{1}{20}\right)^{18} = 10^{-23}$$

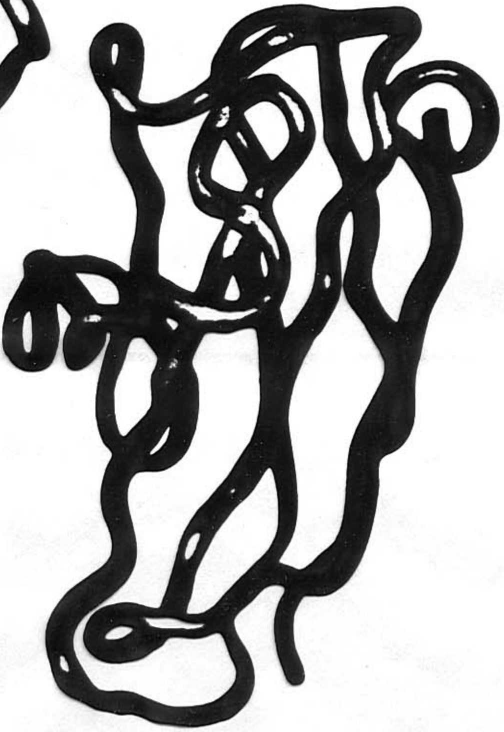
Also, many variations in amino acids don't destroy function

and many different sequences may be interesting

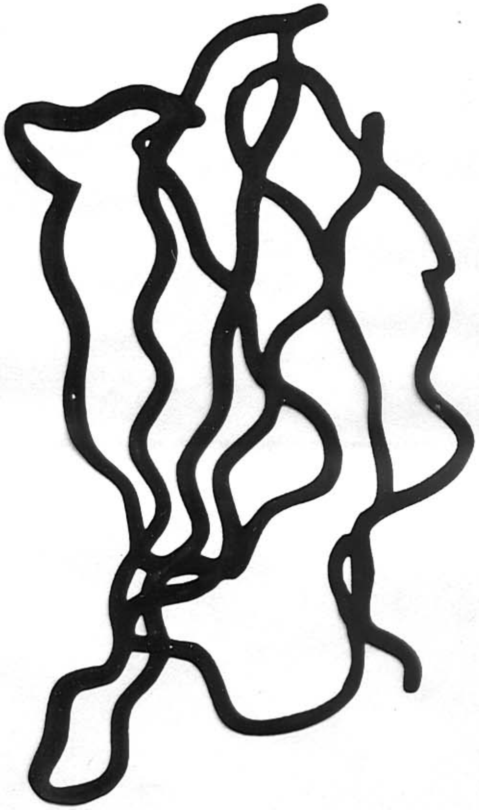
GENETICALLY MOBILE MODULES have been found in many proteins. Two types of these modules, or domains, are shown here. The Fn3 and the GHR domains are examples of fibronectin type III modules. The PapD and CD2 domains are immunoglobulin domains. These modules are linear sequences of amino acids that can fold themselves into consistent, recognizable structures with specific biochemical properties. During evolution, these domains can move as discrete units from one protein to another, which helps new types of proteins to appear.



PapD DOMAIN 1



GHR DOMAIN 1



Fn3 (10TH DOMAIN)

SCIENTIFIC AMERICAN *October 1993*

Summary

- Reactions in atmosphere (Miller-Urey) or sea vents or delivery from space can provide some monomers
- Formation of monomers of proteins easier than for nucleic acids
- Making polymers easier for proteins
- New route for synthesis of nucleotides is promising
- Have to get selection started before polymers get too complex