Fraglets:
Computing with Macromolecules
A Tutorial

BIONETS SP2, Fraglets Workshop

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Tutorial Overview

- Introduction: Original Fraglets, Fraglets in BIONETS
- Fraglets Programming Basics: original and new instructions, examples
- Programming Methodology: breaking down complexity, backwards derivation
- Tools: Automatic code generator (partial), concentration and rate plots, reaction graph
- Exercises
- Summary and Discussion

Fraglets: Background

- Creation around 2001 by C. Tschudin [AINS'03]
  - Inspiration: Molecular biology, cell metabolism, chemical computing (Membrane Computing, Gamma, CHAM), multiset rewriting
- Goals:
  - Automated protocol synthesis and evolution
  - Unified code and data representation (active+passive networking)
  - Efficient packet processing engine: simple instructions with constant (short!) processing time

Fraglets: Background

- Resulting language:
  - **Fraglet** = **computation fragment** = code = data = packet
  - Header tag matching, analogous to packet header processing
  - “Assembly language” of chemical computing: micro-instructions, human-unreadable programs, “write-only” code!

Fraglets in BIONETS

- **On-line evolution**: start from working implementations, continuous self-optimization
  – Resilient execution: resist lost or damaged code portions (resist harmful mutations)
- **Service Evolution**, in addition to Protocol Evolution
  – From a protocol-specific language to a more generic computation model (how generic?)

Fraglets Programming Basics

- Syntax
- Instruction set
- Simple programs

Fraglets Syntax

- Execution environment: multiset of fraglets
  - multiset = unordered set in which elements appear more than once
- Fraglet original syntax: string `n[s1 : s2 : ... : sn]m`
  - n = node where fraglet executes
  - m = multiplicity counter: number of occurences of fraglet in multiset
- New simplified syntax (Dec'06): `n[s1 s2 ... sn]m`
  - ':' now optional
- Goal: simple syntax that can be easily manipulated by automatic means (e.g. genetic programming)

Basic Instruction Set [AINS'03]

Transformation rules: involve a single fraglet

```
[dup t s tail]          --> [t s s tail]     # duplicate symbol
[exch t s1 s2 tail]     --> [t s2 s1 tail]   # swap symbol
[split f1 * f2]         --> [f1], [f2]       # break at '*' position
[nul tail]              --> []               # discard fraglet
a[send ch b tail]       --> b[tail]          # UDP-style send

[new t tail] --> [t n_{i+1} tail]            # new tag creation
                                             # (never implemented?)
```

(!) ':' made optional > fragletsv0.23

Basic Instruction Set [AINS'03]

Reaction rules: involve two fraglets

- Merge if match:

```
[match  t tail1], [t tail2] --> [tail1 tail2]
```

- Persistent match ("catalyst"):

```
[matchp t tail1], [t tail2] --> [matchp t tail1],
                                [tail1 tail2]
```

- Sustain variant:

```
[matchs s t tail1], [s t tail2] --> [tail1 tail2],
                                    [s t tail2]
```

```
# (never implemented?)
```

Other instructions

Fraglets v. 0.18 and 0.19, 2005 (`www.fraglets.net`)

Instructions added after AINS'03 (e.g. WAC'05) or non-documented:

```
[nop tail]    --> [tail]               # nop: do nothing

[wait tail]   --> ...                  # wait: delayed execution
  # (after 10 execution steps:)
... --> [tail]

[pop t x tail] --> [t tail]            # pop: delete symbol
```

Simple Programs

- Rewrite header tag
- Append symbol
- Code Mobility
- Lossy link emulation (WAC'05)

Simple Programs

Rewrite (rename) header tag

```
goal: [in tail] --> [out tail]
solution: [match in out], [in tail] --> [out tail]
```

Append (constant) symbol

```
goal: [in tail] --> [out tail s]
predefined: [store s]
solution: [match in match store out]
trace: [match in match store out], [in tail] -->
  [match store out tail], [store s] -->
  [out tail s]
```

Code Mobility

Read temperature at remote node

```
a a ch
a b ch
f a[send ch b match temp send ch a tempis]

f b[temp 30]
```

Result:

```
f a[tempis 30]
```

Lossy Link Emulation

50% loss on average:

```
a a ch
a b ch
f a[transmit b msg]100
f a[matchp transmit send ch]
f a[matchp transmit nul]
```

Result:

```
f b[msg]44
```

.

Lossy Link Emulation

25% loss on average:

```
a a ch
a b ch
f a[transmit b msg]100
f a[matchp transmit send ch]3
f a[matchp transmit nul]
```

Result:

```
f b[msg]74
```

Easy to emulate other loss patterns, delays (`nop`, `wait`), etc.

New instructions (Dec. 2006, Experimental!)

Basic number manipulation: (currently positive integers only)

```
[length t tail]  --> [t len tail]  # length in symbols
[sum t n m tail] --> [t n+m tail]  # sum two numbers
[lt yes no n m tail] -->           # less than:
  if n < m then [yes n m tail]     # compare two numbers
           else [no  n m tail]
```

Examples:

```
[length t a b c] --> [t 3 a b c]
[sum total 3 4 rest] --> [total 7 rest]
[lt y n 1 2 rest] --> [y 1 2 rest]
[lt y n 9 7 rest] --> [n 9 7 rest]
```

New instructions (Dec. 2006, Experimental!)

```
[copy tail]      --> [tail]2          # copy fraglet

[empty y n tail] -->                  # test if tail empty
  if tail==[] then [y]                # (useful for recursion)
              else [n tail]
```

Examples:

```
[copy this is a fraglet] --> [this is a fraglet]2

[empty finish continue 6 7 8] --> [continue 6 7 8]
[empty finish continue] --> [finish]
```

New instructions (Dec. 2006, Experimental!)

```
# create new symbol:
[newname t s1 s2 tail] --> [t s1s2 tail]

# create new node with communication channel:
[newnode ch node tail] --> a node ch, node[tail]
```

Examples:

```
[newname t myid 10 rest of fr] --> [t myid10 rest of fr]
[newnode ch b init b mycode] --> a b ch, b[init b mycode]
```

More Programs

- Increment counter
- Prepend, append
- Delete from head (reimplement pop)

Increment counter

```
goal: [incr x n] --> [x n+1]
```

How to program: derive code from bottom to top:

```
[matchp incr ......... ], [incr x n] -->
...
...
...
...
[sum x 1 n] --> # step1: find rule that uniquely leads to
[x n+1]         # target result: this rule is: sum 1 to n
```

Resulting program:

```
f [matchp incr ......... ]
```

Increment counter

```
goal: [incr x n] --> [x n+1]
```

How to program: derive code from bottom to top:

```
[matchp incr ......... ], [incr x n] -->
...
[exch sum 1 x n] --> # step2: find rule that uniquely leads
                     # to step1, while pushing input as close as
                     # possible to tail: 'exch' does the job!
[sum x 1 n] -->      # step1: find rule that uniquely leads to
[x n+1]              # target result: this rule is: sum 1 to n
```

Resulting program:

```
f [matchp incr ......... ]
```

Increment counter

```
goal: [incr x n] --> [x n+1]
```

How to program: derive code from bottom to top:

```
[matchp incr exch sum 1], [incr x n] --> # step3: input is
          # now at tail, so just match header tag and done!
[exch sum 1 x n] --> # step2: find rule that uniquely leads
                # to step1, while pushing input as close as
                # possible to tail: 'exch' does the job!
[sum x 1 n] --> # step1: find rule that uniquely leads to
[x n+1]         # target result: this rule is: sum 1 to n
```

Resulting program:

```
f [matchp incr exch sum 1]
```

Prepend fraglet

```
goal: [store 7 8], [prepend 4 5 6] --> [store 4 5 6 7 8]
```

Trace (code derived from bottom to top):

```
[matchp prepend match store store], [prepend 4 5 6] -->
[match store store 4 5 6], [store 7 8] -->
[store 4 5 6 7 8]
```

Resulting program:

```
f [matchp prepend match store store]
```

Append fraglet

```
goal: [store 1 2], [append 3 4 5] --> [store 1 2 3 4 5]
```

Trace (read bottom-up):

```
[matchp append split match store match app1 store * app1],
[append 3 4 5] -->
[split match store match app1 store * app1 3 4 5] -->
[match store match app1 store], [app1 3 4 5]
[match store match app1 store], [store 1 2] -->
[match app1 store 1 2], [app1 3 4 5] -->
[store 1 2 3 4 5]
```

Resulting program:

```
f [matchp append split match store match app1 store * app1]
```

Delete from head (pop)

Goal: reimplement pop instruction (call it 'del')

```
[del tag x tail] --> [tag tail]
```

Trace (backwards derivation, i.e. read bottom-up):

```
[matchp del exch tmp2], [del tag x y z] -->
[matchp tmp2 exch tmp1 * ], [tmp2 x tag y z] -->
[matchp tmp1 split nul], [tmp1 x * tag y z] -->
[split nul x * tag y z] --> [nul x], [tag y z]
```

Program:

```
f [matchp del exch tmp2]
f [matchp tmp2 exch tmp1 * ]
f [matchp tmp1 split nul]
```

Recursion

Count fraglet length (without using "length" rule):

```
[count a b c] --> [total 3] # consumes original fraglet
```

Resulting program:

```
f [counter 0]
f [matchp count empty stop cnt]
f [matchp stop match counter total]
f [matchp cnt pop cnt1]
f [matchp cnt1 split match counter incr counter * count]
```

Recursion

Trace: (!) here forward (top-down) fine!

```
[counter 0]
[matchp count empty stop cnt], [count] --> [total 0]
[matchp count empty stop cnt], [count x tail] -->
  [match counter incr counter], [count tail]
[matchp stop match counter total], [stop] -->
  [match counter total], [counter n] --> [total n]
[matchp cnt pop cnt2], [cnt x tail] -->
  [pop cnt2 x tail] --> [cnt2 tail]
[matchp cnt2 split match counter incr counter * count],
  [cnt2 tail] -->
[split match counter incr counter * count tail] -->
  [match counter incr counter], [count tail] #recursion
```

Programming Methodology

Break down complexity:

- Identify partial goals: write them down in terms of transformations of the form:

  `[intag ...], [...] --> [outtag ...], [...]`

- Recursion = reuse of partial goals (good!)
- Solve each partial goal using bottom-up derivation (parts of it can be automated, see following slides)
- In case of manual derivation, keep traces for future use (because resulting program is generally unreadable!!)

Programming Methodology

- Beware of parallel execution: is your code reentrant?
- Test and debug each partial goal separately
- Test full program: can only work!

Tools

- Automatic Code Generator (partial): `gencode.pl`
- Concentration plot: `concentr.pl`
- Production/Consumption rate: `rate.pl`
- Reaction graph: `log2graph*`

Automated Code Generation with gencode.pl

Goal:

```
input: [tag x tail]
output:
  [frag with x here another x there and again an x tail]
```

Invoke `gencode.pl` script:

```
bin/gencode.pl
tag x
f [frag with x here another x there and again an x]
<CTRL-D>
```

Automated Code Generation with gencode.pl

Output program:

```
f [ matchp tag dup tag_8 ]
f [ matchp tag_8 exch tag_7 an ]
f [ matchp tag_7 exch tag_6 again ]
f [ matchp tag_6 exch tag_5 and ]
f [ matchp tag_5 exch tag_4 there ]
f [ matchp tag_4 dup tag_3 ]
f [ matchp tag_3 exch tag_2 another ]
f [ matchp tag_2 exch tag_1 here ]
f [ matchp tag_1  frag with ]
```

Automated Code Generation with gencode.pl

Execution:

```
f [matchp ...] # paste automatically generated code here
f [tag mysymb rest of fra]   # example input
f [tag yoursymb second test] # another example input
e # execute
```

Result:

```
f [matchp ...] # same matchp rules, omitted
f [frag with mysymb here another mysymb there and again
   an mysymb rest of fra]1
f [frag with yoursymb here another yoursymb there and again
   an yoursymb second test]1
```

Automated Code Generation

- Able to transform an input symbol into any arbitrary output fraglet
- Saves tedious symbol manipulations
- Deterministic code generation, 100% correct by construction (except for bugs in the generator itself...)
- Simple, but useful feature, since this pattern is very common: for example, in RDP (WAC'05):

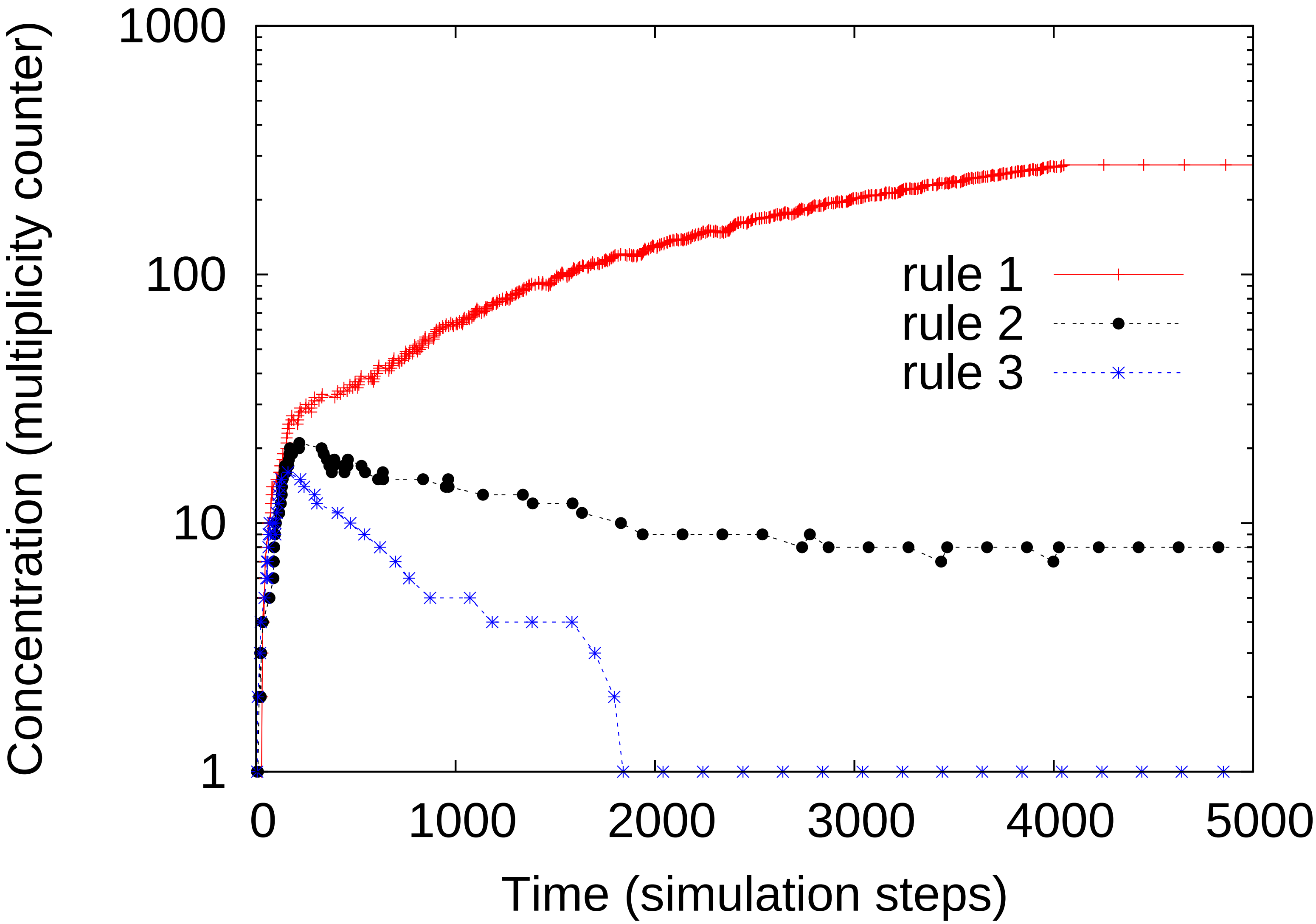
```
[rdp payload] --> [transmit payload], [store payload]
```

  - transmit one copy of payload to destination and store other copy for retransmission in case of loss

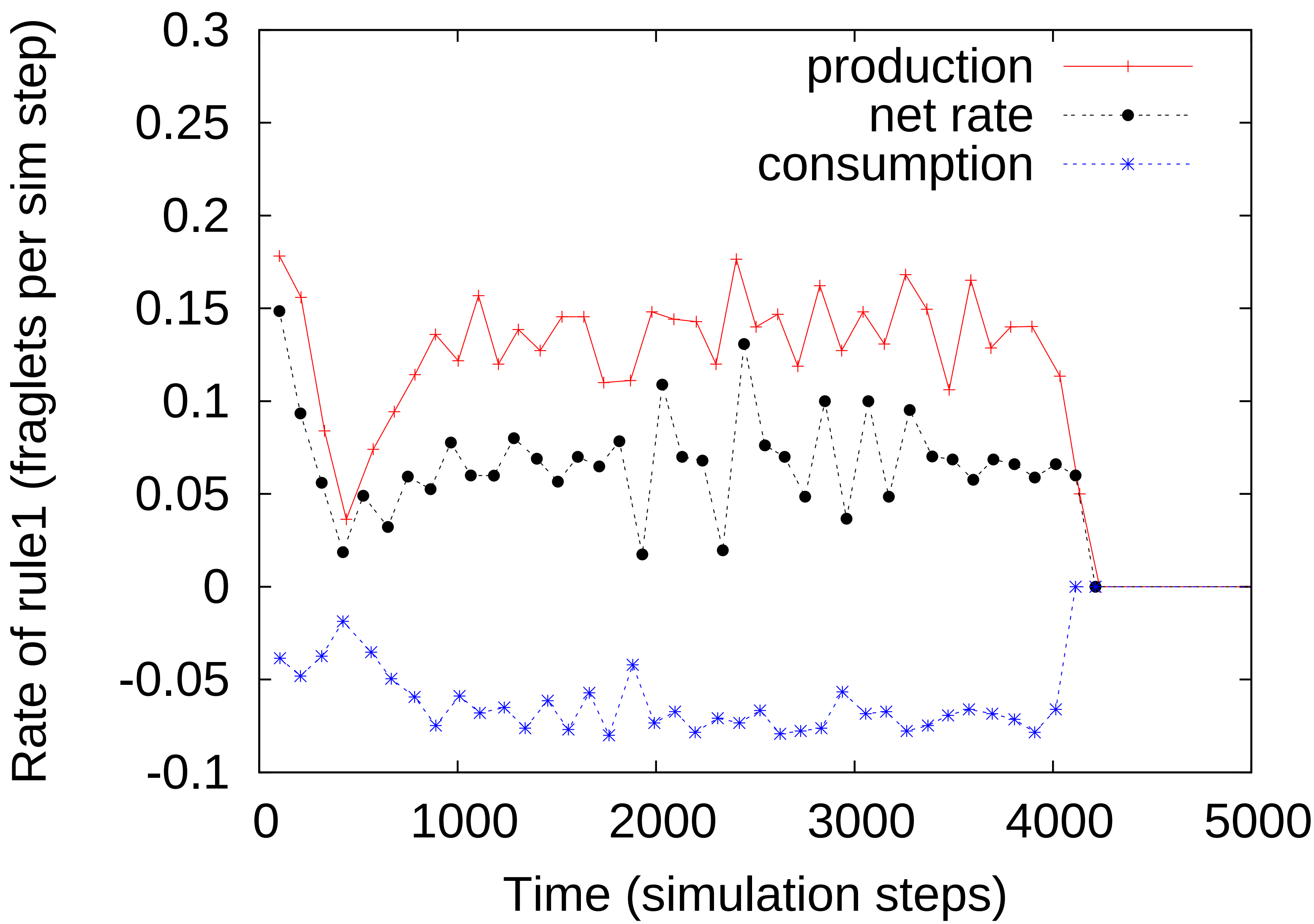
Automated Code Generation

- Recursion supported implicitly (fraglet tail carried along by default)
- Limitations
  - Currently only one input variable supported
  - Implementation maybe not the shortest possible
  - Do we actually *need* such micro-transformations, or is this rather a language limitation? Why not adding features in the language that allow for *any* fraglet to be generated with a single rule?
    - Trade-off: complexity of the language vs. complexity of the interpreter

Concentration Plot: concentr.pl



Rate Plot: rate.pl



Reaction Graph: log2graph* scripts

Exercises (free choice of one or more)

- Get the minimum of a list of numbers

```
[getmin 8 99 4 23] --> [min 4]
```

- Invert a fraglet:

```
[invert a b c] --> [inverted c b a]
```

- Duplicate a fraglet (without using “copy” rule):

```
[mycopy a b c] --> [a b c]2
```

- Multiply two numbers:

```
[multiply result x y] --> [result x*y]
```

Exercises (free choice of one or more)

- Recreate the original 'new' instruction using 'newname' and 'sum' (or 'incr'):

```
[new t tail] --> [t n_{i+1} tail]
```

- Mutate a fraglet at a random position, by inserting, deleting or exchanging a symbol, for example:

```
[mutate a b c] --> [mutated b c]
[mutate a b c] --> [mutated b a c]
[mutate a b c] --> [mutated a a b c]
```

Installing, Compiling and Running Fraglets

```
#unpack:
tar xzvf fraglets0.28.tgz

#compile (if needed)
cd src
make fraglets

#run:
./fraglets -d 3 -e 3 -lim 1000 < myprogram.fra
```

Knoppix CDs available for those without Linux or MacOS.

Solution to Exercise: Getmin

Get the minimum of a list of numbers

Trace:

```
[getmin n]       --> [min2    1 1   n]
[getmin n tail] --> [getmin2 1 len tail]
[min2 1 1 n] --> [min n]
[getmin2 1 len a b rest] --> if a<b [islt a b rest]
                             else   [nlt  a b rest]
[islt a b rest] --> [nlt b a rest]
[nlt a b rest] --> [getmin b rest]
```

Solution to Exercise: Getmin

Program:

```
f [matchp getmin length len1]
f [matchp len1 lt getmin2 min2 1]
f [matchp min2 pop d1]
f [matchp d1 pop min]
f [matchp getmin2 pop d11]
f [matchp d11 pop getmin3]
f [matchp getmin3 lt islt nlt]
f [matchp nlt pop getmin]
f [matchp islt exch nlt]
```

Outlook and Perspectives

- Nice programming model, enticing concepts and programs.
- But code is long, complicated and unreadable by humans: "write-only programs"...
- Fully automated deterministic code generation still impossible.
- Can we generate code by other means, e.g. Genetic Programming?
- Should we have a higher-level, human-oriented chemical programming language?
  - if yes, should it be used standalone or compiled into fraglet code?

Outlook and Perspectives

Why do we need a chemical language at all?

- high parallelism: parallel, alternative execution paths: resilient to program transformations in one path, other paths can take over
  - “rerouting” execution flows
  - must still be verified...
  - is there an alternative for on-line software evolution?