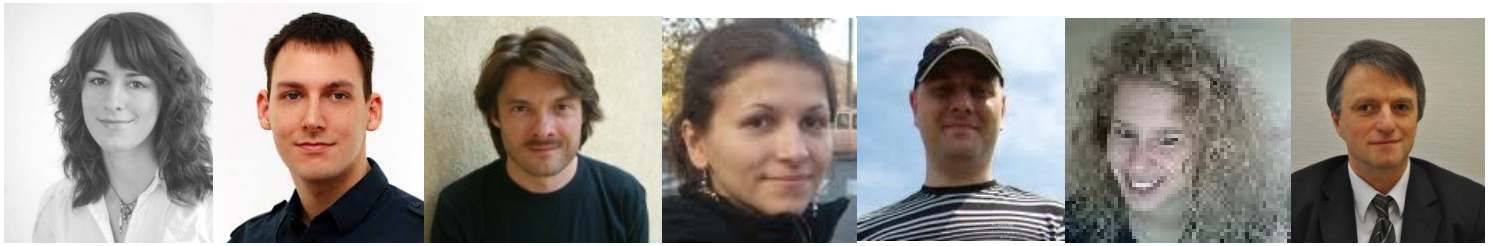
Parallelization by Refactoring

Dept. Programming Languages and Compilers
Eötvös Loránd University, Hungary



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LET'S PARTY!

- Have fun...

LET'S PaRTE!

- Have fun...

LET'S PaRTE!

- Have functional programming!

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LET'S PaRTE!

- Have functional programming!

map-like function speedup prediction

pattern candidate discovery

static analysis task farm

refactoring pipeline parallel patterns

algorithmic skeletons divide and conquer

ParaPhrase Refactoring Tool for Erlang

RefactorErl Wrangler

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Motivation

- Highly heterogeneous mega-core computers
- Performance and energy
- Think parallel
  - High-level programming constructs
  - Deadlocks etc. eliminated by design
  - Communication packaged/abstracted
  - Performance information is part of design
- Restructure existing code

Kevin Hammond

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How shall I parallelize?

- Refactor
  - Use a tool!
  - Guided, semi-automatic transformations
- Experiment
  - Measure, validate
- Repeat
- Applicable for legacy code as well

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Where shall I parallelize?

- Independent computations
- Good potential for speedup
  - Complex computation?
  - Low sequential overhead?
- Find candidates automatically
  - Use a tool!
  - Static program analysis

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Pattern-based parallelism

High-level approach to parallel programming

- Rely on a library of algorithmic skeletons
- Easier to develop code
- Easier to modify / maintain
- Better utilization of resources
  - Static resource management
  - Dynamic resource management

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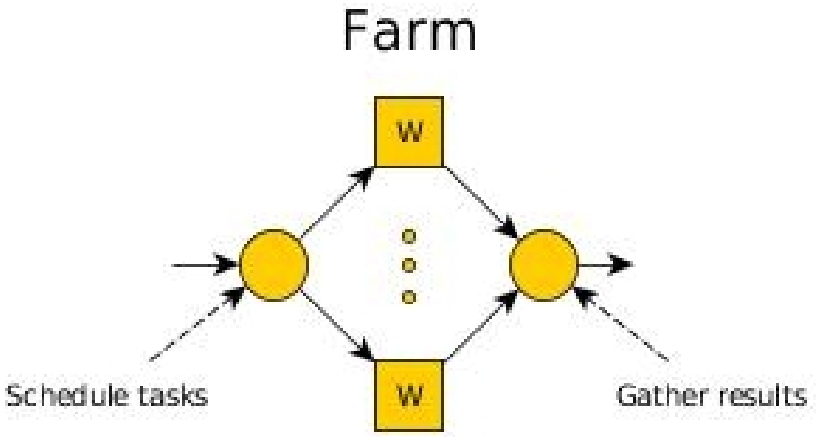

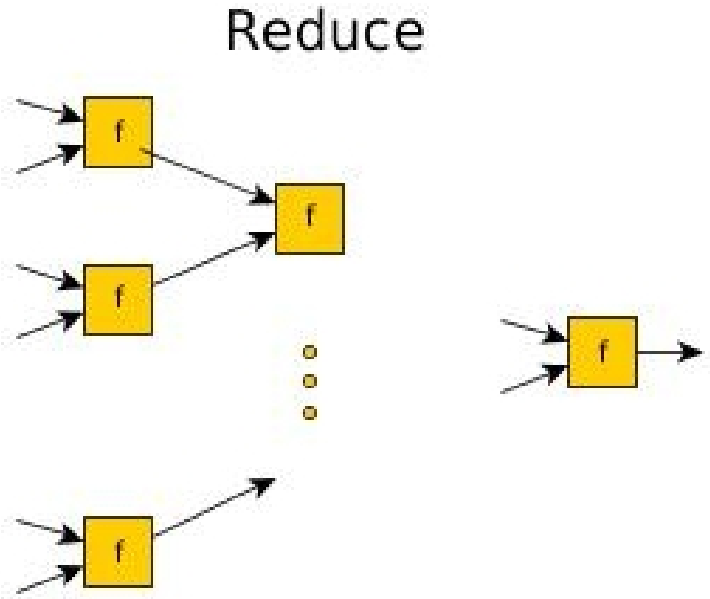

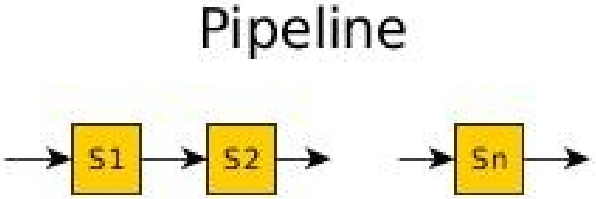

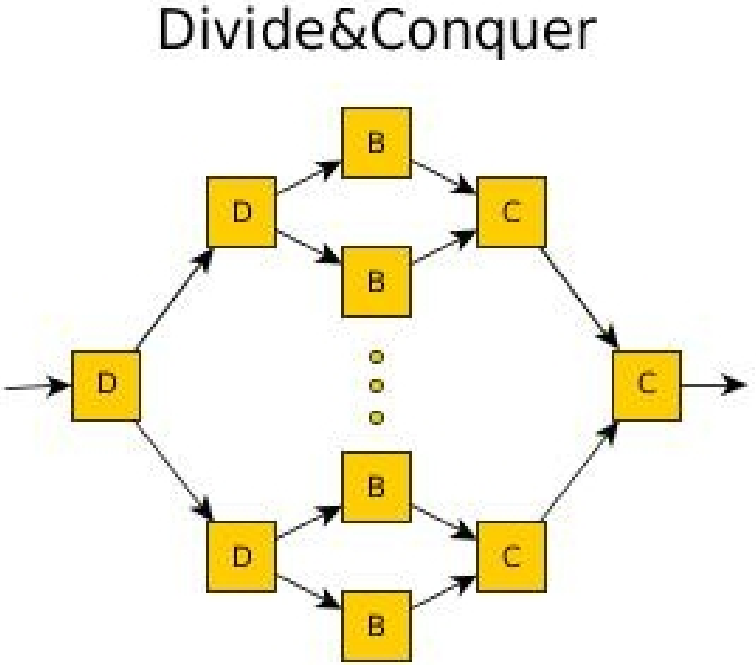

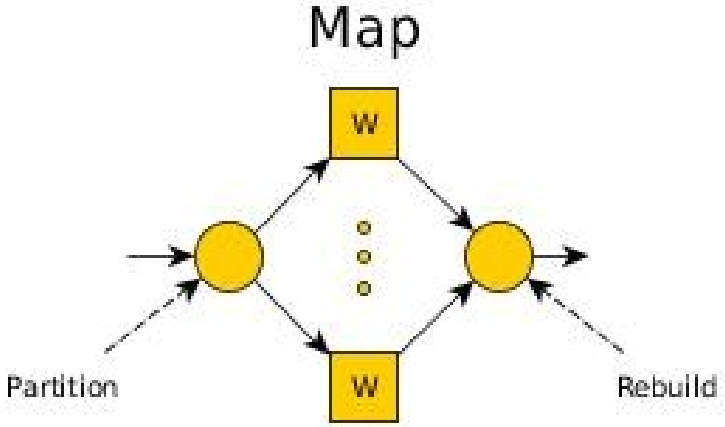

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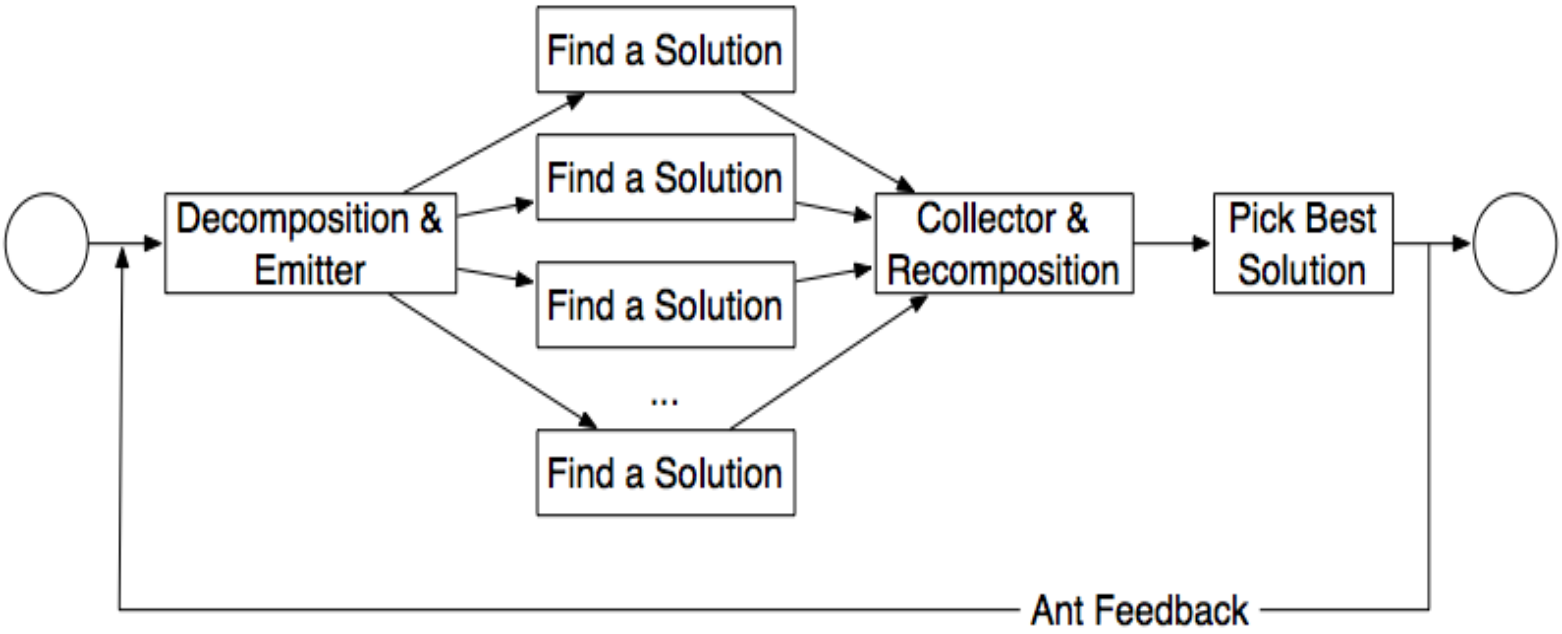
Pool pattern



Ant Colony Optimization

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picture from Kevin Hammond

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Parallel Patterns for Adaptive Heterogeneous Multicore Systems

- Programmability of heterogeneous parallel architectures
- Structured design and implementation of parallelism
- High-level parallel patterns
- Dynamic (re)mapping on heterogeneous hardware

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University of St Andrews

ROBERT GORDON UNIVERSITY·ABERDEEN

National College of Ireland

Cloud Competency Center

ELTE Soft

Queen's University Belfast

AGH

AGH University PL

Erlang SOLUTIONS

UNIVERSITÀ DEGLI STUDI DI TORINO

ALMA UNIVERSITAS TAURINENSIS

UNIVERSITÀ DI PISA

Universität Stuttgart

HLRS

Mellanox TECHNOLOGIES

scch software competence center hagenberg

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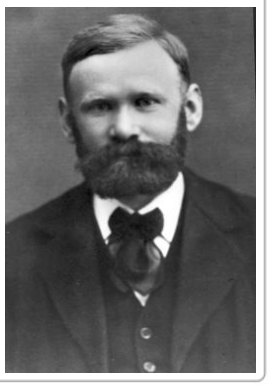
- functional language
- strict, impure, dynamically typed
- concurrency, actor model
- distribution
- fault tolerance
- Open Telecom Platform



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Companies using Erlang

SMARKETS

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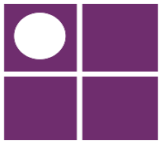
Products using Erlang



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Let's PaRTE!

Assist parallelization of Erlang code with the

ParaPhrase Refactoring Tool for Erlang

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So what is Erlang like?

- Functional (strict, impure, dynamically typed)
- Garbage collected
- Designed for concurrency and distribution
  - Lightweight processes
  - Actor model (message passing)
- Processing binary data
- Fault tolerance (failure recovery)
- Compiles to **`beam`**, runs in VM
- Hot code swap

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Erlang: a functional language

- Variables bound only once
- Recursion instead of loops
  - Tail recursive
- Higher-order functions instead of recursion
- Lambdas, pattern matching
- Properties
  - Strict evaluation (call-by-value)
  - Impurity (e.g. communication)
  - No partial applications

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Terms

- Literals, e.g. `42` or `42.0`
- Atoms, e.g. `leaf`, `blue`, `ok`, `error`, `true`
- Compound data

Funs	`fun(X)-> X+1 end`
Lists	`[0,1,1,2,3,5,8,13,21]`
Tuples	`{may, 10, 2014}`
Records	`#date{month=june,day=7,year=2015}`
Binaries	`<<0,1,1,2,3,5,8,13,21>>`

- Pids, ports, refs

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A complex term

```
[
    {
        farm,
        [
            {
                pipe,
                [
                    {seq, fun scan/1},
                    {seq, fun parse/1}
                ]
            }
        ],
        12
    }
]
```

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Expressions

- Terms (literals, atoms, compound data)
- Variables, e.g. `X`, `Long_Variable_Name`
- Function/operator calls, e.g. `fib(N-1)+fib(N-2)`
- Data structures, e.g. `{june,Day,fib(18)-569}`
- Control structures
  - Branching (**`case`** and **`if`**)
  - Sending and receiving a message
  - Error handling

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Defining a named function

```
increment(N) -> N+1.
```

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Pattern matching

```
fib(N) ->
    case N of
        0 -> 0;
        1 -> 1;
        _ -> fib(N-1) + fib(N-2)
    end.
```

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Multiple function clauses

```
fib(0) -> 0;
fib(1) -> 1;
fib(N) -> fib(N-1) + fib(N-2).
```

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Guards

```
fib(N) when N < 2 -> N;
fib(N) -> fib(N-1) + fib(N-2).
```

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Using an `if`-expression

```
fib(N) ->
    if
        N < 2 -> N;
        true  -> fib(N-1) + fib(N-2)
    end.
```

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Recursion

```
factorial(1) -> 1;
factorial(N) -> N * factorial(N-1).
```

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Tail recursion

```
factorial(1) -> 1;
factorial(N) -> N * factorial(N-1).
```

```
factorial(N) -> factorial_acc(N,1).

factorial_acc(1,Acc) ->
  Acc;
factorial_acc(N,Acc) ->
  factorial_acc(N-1, Acc*N).
```

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Overloading on arity

```
prime(1) -> false;
prime(N) when N > 1 -> prime(N,2).

% no proper divisors of N
% between M and sqrt(N)

prime(N,M) ->
   M*M>N orelse ( N rem M =/= 0 andalso
                  prime(N,M+1)
                ).
```

- Overloaded functions `prime/1` and `prime/2`
- `prime/2` is helper function

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Lists

```
[0,1,1,2,3,5,8]
[0 | [1,1,2,3,5,8]]
[0 | [1 | [1 | [2 | [3 | [5 | [8 | []]]]]]]]
[0,1,1,2 | [3 | [5 | [8 | []]]]]
[0,1,1,2 | [3,5,8]]
```

- `[Head | Tail]` notation
- List comprehension

```
[N || N <- lists:seq(1,100), prime(N)]
```

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Scalar-vector multiplication

```
mul(Scalar,[]) -> [];
mul(Scalar,[Head|Tail]) ->
   [ Scalar*Head | mul(Scalar,Tail) ].
```

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Scalar-vector multiplication

```
mul(Scalar,[]) -> [];
mul(Scalar,[Head|Tail]) ->
   [ Scalar*Head | mul(Scalar,Tail) ].
```

```
mul(Scalar,List) ->
   [ Scalar*Item || Item <- List ].
```

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Scalar-vector multiplication

```
mul(Scalar,[]) -> [];
mul(Scalar,[Head|Tail]) ->
   [ Scalar*Head | mul(Scalar,Tail) ].
```

```
mul(Scalar,List) ->
   [ Scalar*Item || Item <- List ].
```

```
mul(Scalar,List) ->
   map( fun(Item) -> Scalar*Item end, List ).
```

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Higher-order functions

```
map(Fun,[]) -> [];
map(Fun,[Head|Tail]) ->
   [ Fun(Head) | map(Fun,Tail) ].

filter(Pred,List) ->
   [ Item || Item <- List, Pred(Item) ]
```

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fun-expressions

```
map(  fun(Item) -> Scalar*Item end, List )
```

```
filter( fun prime/1, List )
```

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Variable binding

- Formal parameters:

```
fib(N)-> ...
mul(Scalar,[Head|Tail])-> ...
```

- Generator in list comprehension:

```
[ ... | Item <- List]
```

- Pattern matching expression

  Syntax: `Pattern = Expression`

  Primes = primes(List)

  [Head | Tail] = primes(List)

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Sequence of expressions

```
area( {square, Side} ) ->
    Side * Side;

area( {circle, Radius} ) ->
    % almost :-)
    3.14 * Radius * Radius;

area( {triangle, A, B, C} ) ->
    S = (A + B + C)/2,
    math:sqrt(S*(S-A)*(S-B)*(S-C)).
```

- from http://www.erlang.org/course/course.html
- Grouping with **`begin`** ... **`end`**

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Modules

- Code in `.hrl` and `.erl` files
- Compilation unit: *module*
- Modules contain *forms*
  (e.g. function and macro defs)

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Example: mymath.erl

```
-module(mymath).

-export([fib/1,prime/1,pi/0]).

-define(PI,3.14).

pi() -> ?PI.

fib(N) when N<2 -> N;
fib(N) -> fib(N-1) + fib(N-2).

prime(1) -> false;
prime(N) when N > 1 -> prime(N,2).

prime(N,M) when M*M > N -> true;
prime(N,M) when N rem M == 0 -> false;
prime(N,M) -> prime(N,M+1).
```

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Calling functions

- Full name of exported functions:
  `mymath:prime/1`
- They can be called from other modules:
  `mymath:prime(1987)`
- They can be imported and called without module prefix
- Many built-in functions (BIFs) are auto-imported
- Calling through a variable:
  `F = fun mymath:prime/1, F(1987)`
- Dynamic call: `apply(Module,Function,Args)`

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Compiling and running

```
$ ls mymath.erl
mymath.erl
$ erl
Erlang R16B (erts-5.10.1) [source] [smp:4:4]
[async-threads:10] [hipe] [kernel-poll:false]

Eshell V5.10.1 (abort with ^G)
1> c(mymath).
{ok,mymath}
2> mymath:prime(1987).
true
3> q().
ok
4> $ ls mymath*
mymath.beam mymath.erl
```

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What else?

- Concurrency, distributed programming
  - processes, ports, nodes
  - sending and receiving messages
- Exception handling
- Standard libraries, OTP
- Programming patterns (behaviors)

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Coming back to PaRTE...

Assist parallelization of Erlang code with the

ParaPhrase Refactoring Tool for Erlang

- Discover parallelizable code fragments
- Predict speedup, make suggestions
- Perform guided automated refactorings
- Pattern-based parallelism

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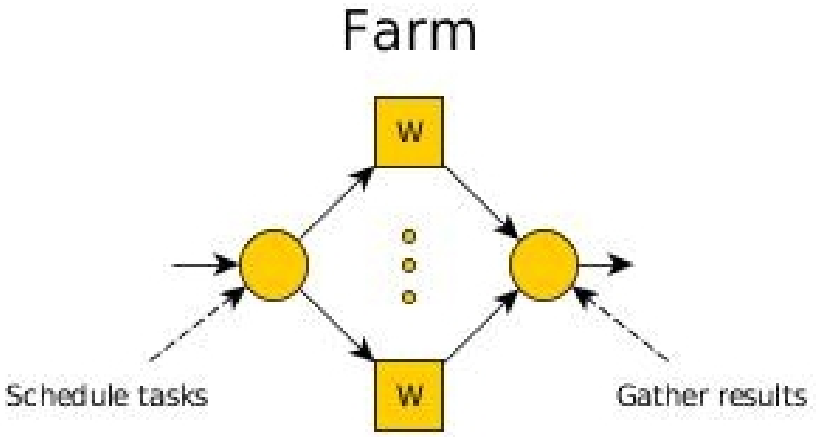

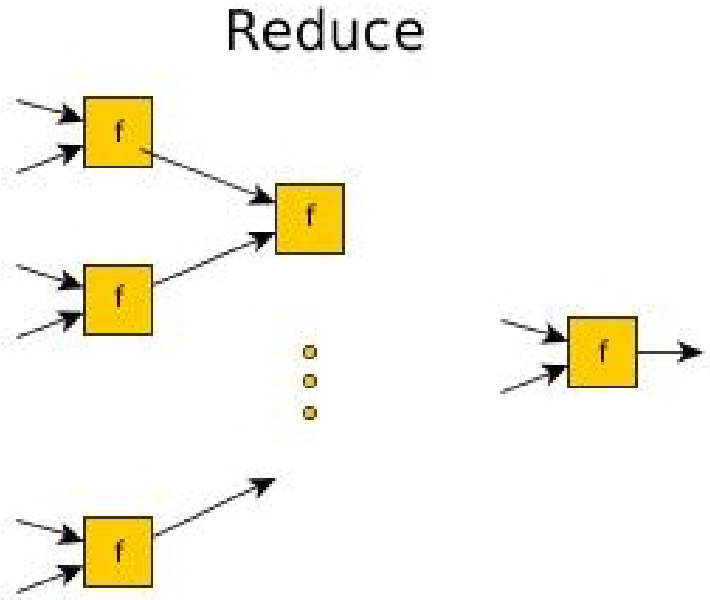

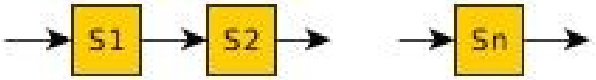

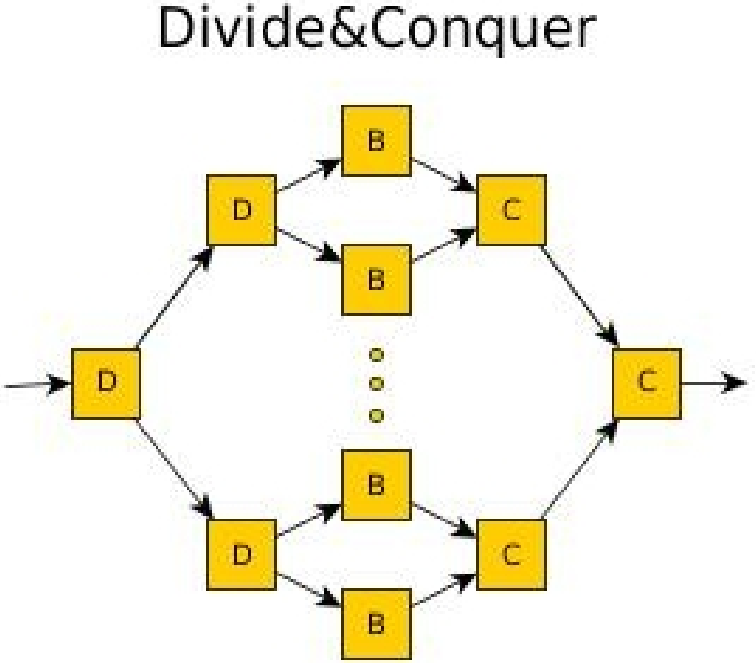

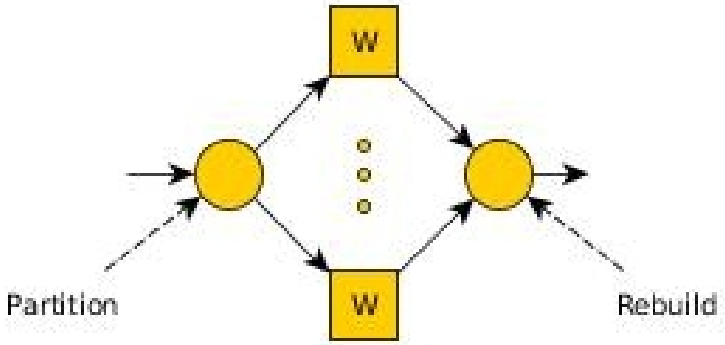

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Parallel skeletons

http://paraphrase-ict.eu/Deliverables/deliverable-2.6

The **skel** library

- Basic algorithmic skeletons
  farm, pipe, map, reduce, ord, feedback etc.
- High-level patterns: skel hlp
  dc, evolutionPool etc.
- Heterogeneous skeletons: Lapedo
  OpenCL kernels for CPU and GPU

  http://paraphrase-ict.eu/Deliverables/d27prototype.tar.gz

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Example: parsing modules

```
[ parse ( scan ( read ( Module ) ) )
                    || Module <- Modules ]
```

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Example: parsing modules

```
[ parse ( scan ( read ( Module ) ) )
                        || Module <- Modules ]


skel:do([
  { farm, [{ pipe, [ { seq, fun read/1  },
                     { seq, fun scan/1  },
                     { seq, fun parse/1 }
                   ] }
           ], 5 }
  ], Modules )
```

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Example: radix sort

```
sort( List ) -> sort(List,0).

sort( List,   _    ) when length(List) < 2 ->
   List;

sort( List, Level ) ->
   lists:append(
      [ sort( Bucket, Level+1 )
        || Bucket <- divide( List, Level )
      ]
   ).

divide( List, Level ) -> ...
```

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Divide-and-conquer pattern

```
{ dc, IsBase, BaseFun, Divide, Combine }


{ dc, IsBase, BaseFun, Divide, Combine,
  MaxProcesses }


SEQ_DC =
{ seq_dc, IsBase, BaseFun, Divide, Combine },
PAR_DC =
{ dc, IsSeq, SEQ_DC, Divide, Combine }
```

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Example: radix sort

```
sort( List ) -> skel:do( [{ dc,
      fun({Lst,Level}) -> length(Lst) < 2 end,
      fun({Lst,Level}) -> Lst end,
      fun({Lst,Level}) ->
            [ {Bucket,Level+1}
              || Bucket <- divide(Lst, Level)
            ]
         end,
      fun lists:append/1
  }], {List,0}).
```

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Example: radix sort

```
sort( List ) -> sk_hlp:dc(
      fun({Lst,Level}) -> length(Lst) < 2 end,
      fun({Lst,Level}) -> Lst end,
      fun({Lst,Level}) ->
            [ {Bucket,Level+1}
              || Bucket <- divide(Lst, Level)
            ]
         end,
      fun lists:append/1
   )  ({List,0}).
```

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ParaPhrase approach

- Identify (strongly hygienic) components
- Discover patterns of parallelism
- Structure the components into a parallel program
  - Turn the patterns into concrete code (skeletons)
  - Take performance, energy etc. into account
- Restructure if necessary
- Use a refactoring tool

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Effectiveness of the approach

Parallelization	Manual	ParaPhrasing
Convolution	3 days	3 hours
Ant Colony	1 day	1 hour
BasicN2	5 days	5 hours
Graphical Lasso	12 hours	2 hours

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PaRTE

ParaPhrase Refactoring Tool for Erlang

- Locate parallel pattern candidates
- Estimate speedup for different configurations
- Advise programmer
- Assist with refactoring
- Enforce preservation of functionality

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Googling the code for patterns

Pattern Candidate Browser

Transformation sequences

ID	Configuration	Module	Function	Arity	Number of workers	Expected speedup (CPU)	Expected speedup (GPU)	Recommended?
1	(Δe295)	matrix_ex_paper	mult_matrix2	2	12	11,99	1,00	✓
2	(Δe243)	matrix_ex_paper	mult_matrix	2	12	10,80	1,00	✓
6	(Δ(Δe337))	matrix_ex_paper	mult_matrix2	2	12	6,58	1,00	✓
3	(Δ(Δe337))	matrix_ex_paper	mult_matrix	2	12	6,58	1,00	✓
5	(Δe292)	matrix_ex_paper	mult_matrix2	2	12	2,98	1,00	✓
4	(Δe337)	matrix_ex_paper	scalar_product	2	12	1,06	1,00	✓

Chart options

Apply selected transformations

Details of the transformation sequence

Configuration	Location information	Program text	Number of workers	Sequential CPU time	Sequential GPU time	Parallel CPU time	Parallel GPU time	Expected speedup (CPU)	Expected speedup (GPU)	Used stream length
e337	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{18,15},{18,25}} - {{18, 30}, {18, 30}}	mult_scalar(A,B)	1	0,14	0,00	0,14	0,00	1,00	1,00	1
(Δe337)	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{18,13},{18,13}} - {{19, 39}, {19, 39}}	[mult_scalar(A,B) || {A,B} <- lists:zip(R,C)]	1	1 375,42	0,00	2 506,26	0,00	0,55	1,00	10 000
(Δ(Δe337))	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{6,3},{6,3}} - {{7, 26}, {7, 26}}	[scalar_product(R,C) || R <- Rows, C <- Cols]	12	13 754 154,08	0,00	2 091 407,67	0,00	6,58	1,00	10 000

Chart options

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ern Candidate Browser

nsformation sequences

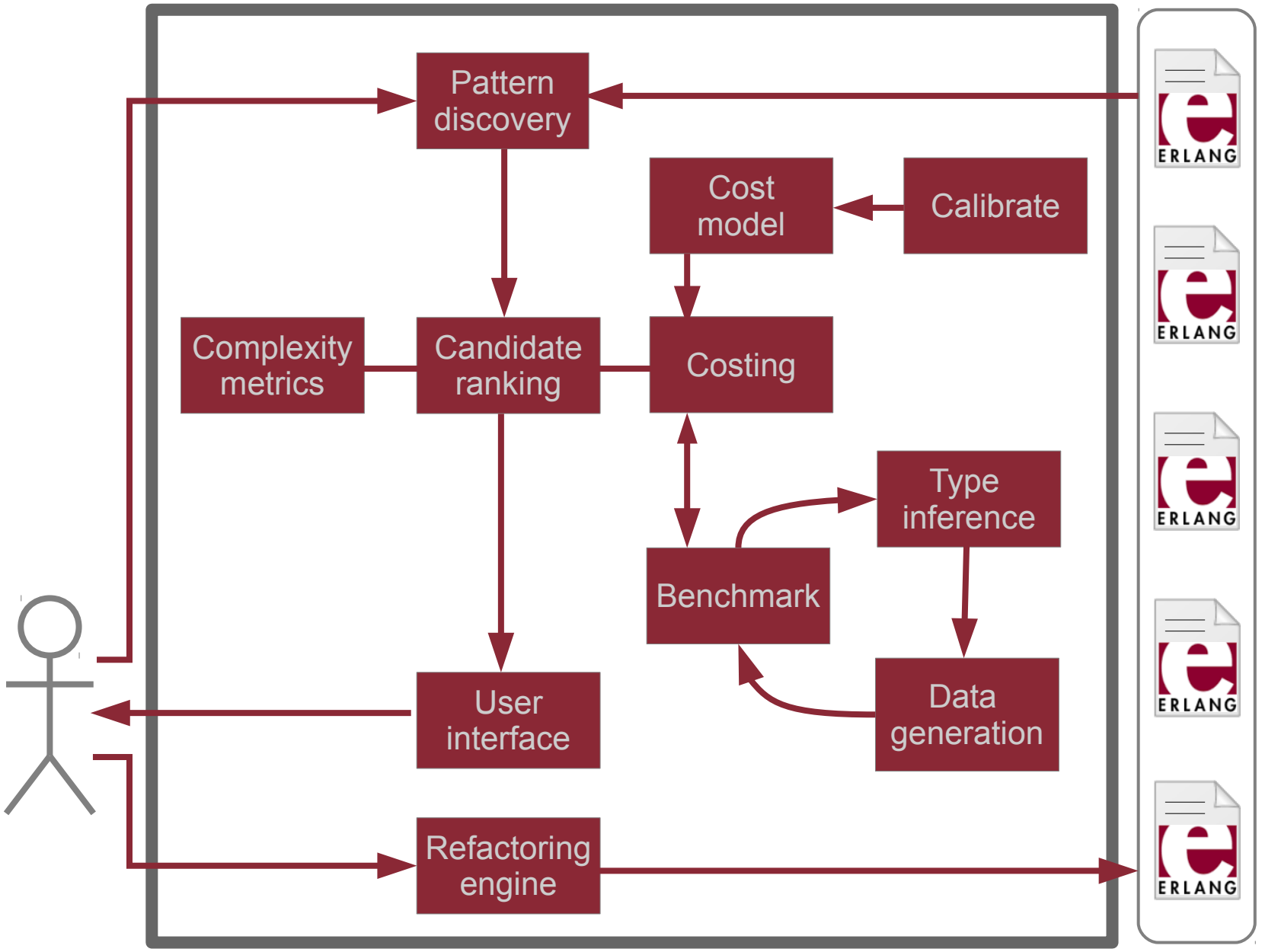
Configuration	Module	Function	Arity	Number of workers	Expected speedup (CPU)
(Δe295)	matrix_ex_paper	mult_matrix2	2	12	11,99
(Δe243)	matrix_ex_paper	mult_matrix	2	12	10,80
(Δ(Δe337))	matrix_ex_paper	mult_matrix2	2	12	6,58
(Δ(Δe337))	matrix_ex_paper	mult_matrix	2	12	6,58
(Δe292)	matrix_ex_paper	mult_matrix2	2	12	2,98
(Δe337)	matrix_ex_paper	scalar_product	2	12	1,06

t options

ls of the transformation sequence

guration	Location information	Program text	Number of workers	Sequential CPU time	Sequential GPU time	Para CPU t
	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{18,15},{18,25}} - {{18, 30}, {18, 30}}	mult_scalar(A,B)	1	0,14	0,00	
7)	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{18,13},{18,13}} - {{19, 39}, {19, 39}}	[mult_scalar(A,B) || {A,B} <- lists:zip(R,C)]	1	1 375,42	0,00	2
337))	/Users/V/paraphrase/referl/tool/matrix/matrix_ex_paper.erl : {{6,3},{6,3}} - {{7, 26}, {7, 26}}	[scalar_product(R,C) || R <- Rows, C <- Cols]	12	13 754 154,08	0,00	2 091

t options



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Pattern candidate discovery

- Collect syntactic & semantic information
  - List comprehensions
  - Library calls (`lists:map/2`)
  - Recursion structure
  - Side conditions
- Task farm, pipeline, divide-and-conquer, feedback
- Heuristics

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Task farm

```
[ parse(scan(read( Module )))
                        || Module <- Modules ]
```

```
Work = fun(Module) ->
           parse(scan(read(Module))) end,
skel:do([{farm,[{seq,Work}],5}], Modules)
```

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Pipeline

```
[ parse(scan(read( Module )))
                        || Module <- Modules ]
```

```
Stages =
   [{seq,read/1},{seq,scan/1},{seq,parse/1}],
skel:do([{pipe,Stages}], Modules)
```

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Farm of pipes

```
[ parse(scan(read( Module )))
                        || Module <- Modules ]
```

```
Stages =
   [{seq,read/1},{seq,scan/1},{seq,parse/1}],
Work = {pipe,Stages},
skel:do([{farm,Work,5}], Modules)
```

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Functional “quicksort”: d&c

```
qs ( List ) ->
  case List of
    []    -> [] ;
    [H|T] ->
       {List1,List2} = lists:partition(
                          fun(X) -> X < H end,
                          T),
       qs(List1) ++ [H] ++ qs(List2)
  end.
```

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Karatsuba: d&c

```
karatsuba( Num1 , Num2 ) ->
    ...
    Z0 = karatsuba( Low1 , Low2 ),
    Z1 = karatsuba( add(Low1,High1),
                    add(Low2,High2) ),
    Z2 = karatsuba( High1 , High2 ),
    ...
```

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Radix sort: d&c

```
sort( []  ,   _    ) -> [] ;
sort( [V] ,   _    ) -> [V] ;
sort( List, Level ) ->
  Buckets = divide( List, Level ),
  SortedLists =
    lists:map( fun(B) -> sort(B,Level+1) end,
               Buckets ),
  lists:append( SortedLists ).
```

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Minimax: d&c

```
mm_max( Node, Depth ) ->
  case Depth == 0 orelse terminal(Node)
    true  -> value ( Node ) ;
    false -> lists:max([ mm_min(C, Depth-1)
                       || C <- children(Node)
                       ])
  end.

mm_min( Node, Depth ) -> ... mm_max ...
```

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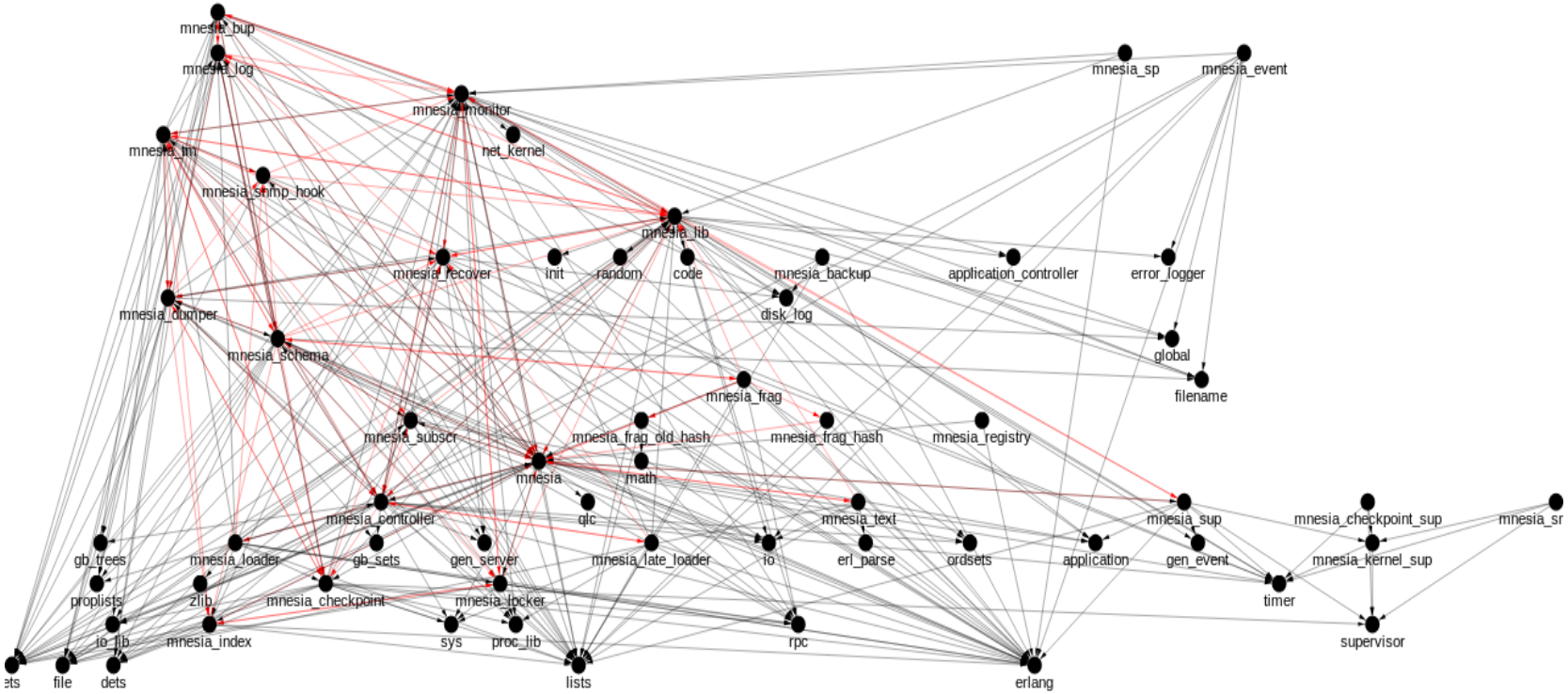
RefactorErl

Static source code analyzer and transformer

http://plc.inf.elte.hu/erlang



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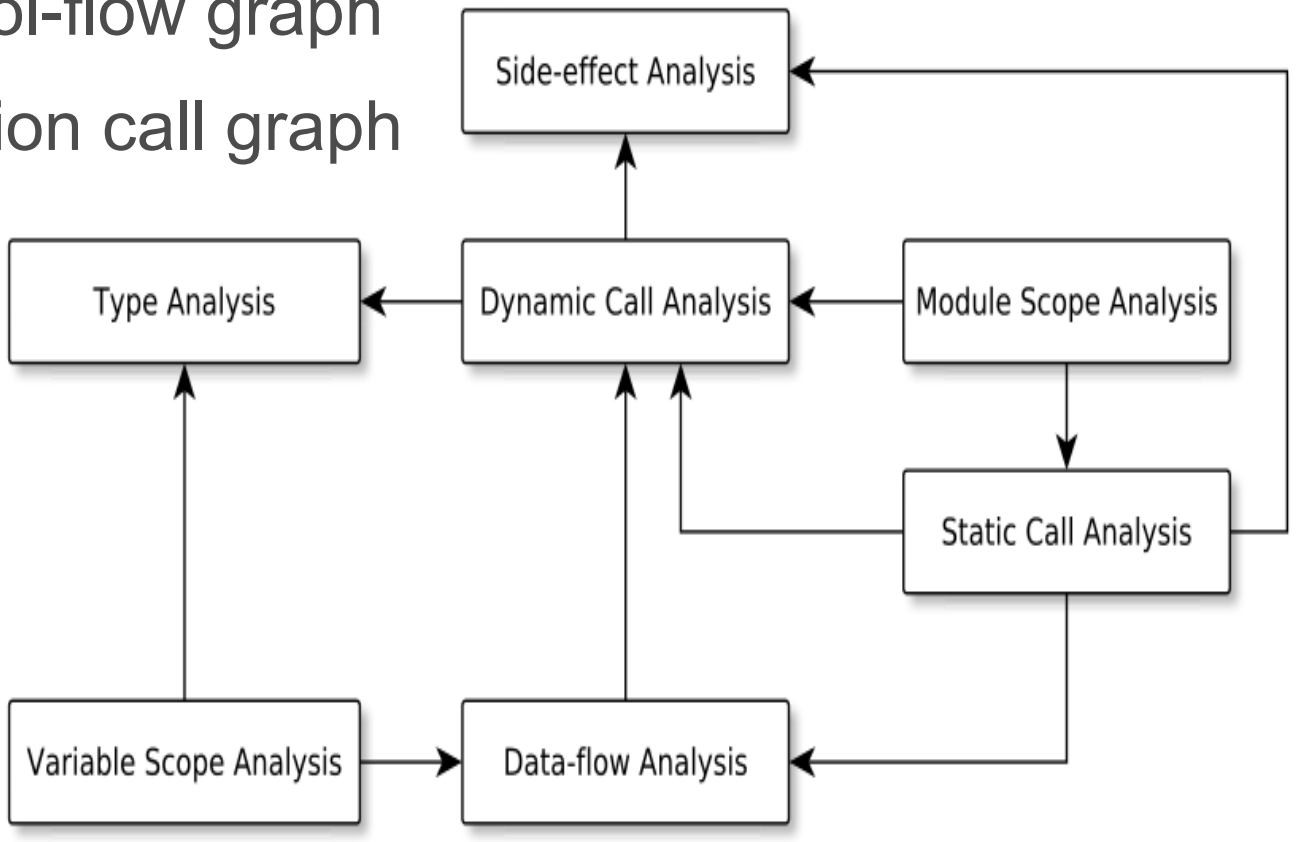
Standard static analyses

- Data-flow graph
- Control-flow graph
- Function call graph



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Pattern-specific analyses

- Identify components
  - Side effects
- Identify patterns
  - Data dependency

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Component

Action performed by Worker (farm) or Stage (pipe)

- Side-effect analysis
  - Message passing
  - NIFs and global variables
  - ETS etc.
  - Process dictionary, node names
  - Exceptions
- Hygiene rather than purity

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Hygienic component

- Identify used resources
- Classify read/alter operations

  $use(C, R) \in \{ No, Read, Alter \}$

- Component set:
  components executed in parallel

$$\forall R \quad \forall C_1 \neq C_2 \in S:$$
$$use(C_1, R) = Alter \rightarrow use(C_2, R) = No$$

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Element-wise processing

```
[ parse(scan(read( Module )))
                        || Module <- Modules ]
```

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Element-wise processing

```
[ parse(scan(read( Module )))
                        || Module <- Modules ]
```

```
Work = fun(Module) ->
           parse(scan(read(Module))) end,
lists:map(Work,Modules)
```

```
psr([]) -> [];
psr([H|T]) -> [parse(scan(read(H)))|psr(T)].
          ... psr(Modules) ...
```

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Element-wise processing

```
f(P1, P2, P3, P4) ->
   case P3 of
      [] -> [];
      [ Head | Tail ] ->
         X = ... Head ... ,
         [ X | f(P1,P2,Tail,P4) ]
   end.
```

a map-like function

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Element-wise processing

```
f(P1, P2, P3, P4) ->
   case P3 of
      [] -> [];
      [ Head | Tail ] ->
         X = ... Head ... ,
         [ X | f(P1,P2,Tail,P4) ]
   end.
```

a map-like function

- *f* must be recursive:

  the interprocedural CFG must contain an execution path from the "starting node" of *f* to a "call-node" of *f*

  $\exists p \in EP(start_f)$ such that $call_f \in p$

- ... base case ... single recursive call ... regularities ... ... data dependencies ... compact data flow reaching ...

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Divide-and-conquer

- A function has multiple recursive calls to itself
- The arguments of a recursive call do not depend on the result of another recursive call

Costly!

- *f must be recursive:*

  the interprocedural CFG must contain an execution path from the "starting node" of *f* to a "call-node" of *f*

  $\exists p \in EP(start_f)$ such that $call_f \in p$

- etc.

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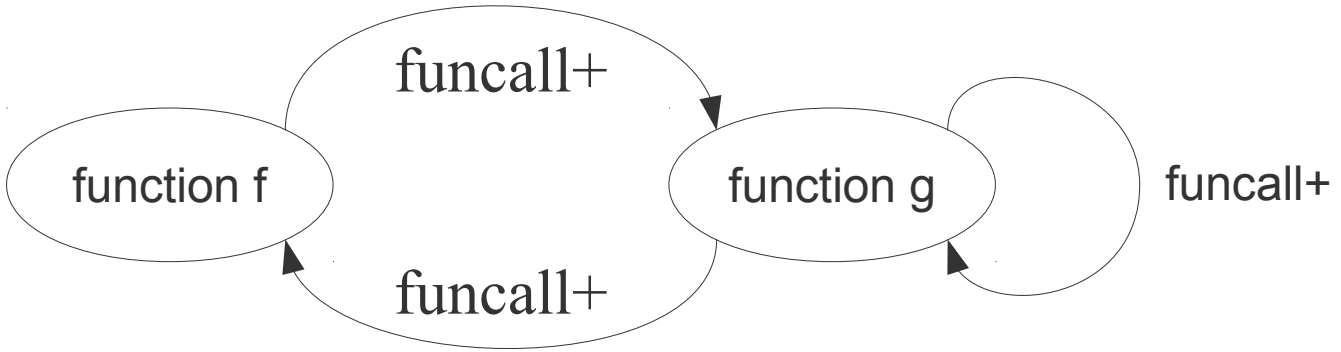
Faster rules

- If *h* operates on lists, and
  - contains list comprehension with *h* in head
  - passes *h* to *lists:map/2* or a map-like function
- Analyze the function call graph



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Experiments

- Ant Colony Optimization
  - Single Machine Total Weighted Tardiness Problem
- Image merging case study
- Intensional Computing Engine
  - Evaluator of the abstract syntax tree of ICE
- Evolutionary Multi-Agent Systems framework
- Thorn
  - Map-reduce framework
- Mnesia
  - Distributed database management system
- RefactorErl core
  - Static program analysis&transformation framework

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Problem sizes

	ELOC	Functions	Files
Ant Colony Optimization	483	56	21
Image merging	779	104	6
ICE evaluator	1094	141	21
Thorn	1313	158	15
EMAS framework	1646	177	25
RefactorErl core	19694	1534	53
Mnesia	22653	1693	31

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Discovery results

	farm	pipe	reduce	d&c	pool
Ant Colony Optimization	10				
Image merging	34	4	2		
ICE evaluator	7		4		
Thorn	17		5		
EMAS framework	71	20	16		9
RefactorErl core	486	49	55	31	
Mnesia	135	8	36	57	2

Map-like functions: 9

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Some interesting candidates

- map-like functions
- divide-and-conquer algorithms

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Map-like function (Mnesia)

```
reverse([]) -> [];
reverse([ H=#commit{ ram_copies      = Ram,
                     disc_copies     = DC,
                     disc_only_copies= DOC,
                     snmp            = Snmp }
        | R ]) ->
  [ H#commit{
     ram_copies      = lists:reverse(Ram),
     disc_copies     = lists:reverse(DC),
     disc_only_copies = lists:reverse(DOC),
     snmp            = lists:reverse(Snmp)
    }
  | reverse(R) ].
```

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Map-like function (EMAS)

```
count_funstats(_,[]) -> [];

count_funstats(
      Agents,
      [{Stat, MapFun, ReduceFun, OldAcc} | T]
    ) ->

    NewAcc =
       lists:foldl( ReduceFun, OldAcc,
          [MapFun(Agent) || Agent <- Agents] ),

    [ {Stat, MapFun, ReduceFun, NewAcc}
      | count_funstats(Agents,T)
    ].
```

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D&C (RefactorErl)

```
...
listcons_length(N, #expr{}) ->
  Ns = ?Dataflow:?reach([N], [back], true),
  L1 = [N2 || N2 <- Ns, N2 /= N,
              ?Graph:class(N2) == expr],
  {L2, L3} = lists:partition(
                    fun is_cons_expr/1, L1 ),
  if L2 == [] orelse L3 /= [] ->
       incalculable;
     true ->
       lists:append(lists:map(
                  fun listcons_length/1, L2))
  end;
...
```

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Another D&C (RefactorErl)

```
realtoken_neighbour(Node, DirFun, DownFun) ->
  case lists:member(?Graph:class(Node),[clause,expr,form,typexp,lex]) of
    false -> no;
    _     -> case ?Syn:parent(Node) of
               []           -> no;
               [{_,Parent}] -> case lists:dropwhile( fun({_T,N}) -> N/=Node end,
                                                     DirFun(?Syn:children(Parent))
                                                   ) of
                                  [{_,Node},{_,NextNode}|_] -> DownFun(NextNode);
                                  _                         ->
                                     realtoken_neighbour(Parent, DirFun, DownFun)
                               end;
               Parents      -> realtoken_neighbour_( Parents, DownFun(Node),
                                                     DirFun, DownFun )
             end
  end.

% Implementation helper function for realtoken_neighbour/3

realtoken_neighbour_([], _FirstLeaf,_DirFun,_DownFun) -> no;
realtoken_neighbour_([{_,Parent}|Parents], FirstLeaf, DirFun, DownFun) ->
  case realtoken_neighbour(Parent, DirFun, DownFun) of
    FirstLeaf -> realtoken_neighbour_(Parents, FirstLeaf, DirFun, DownFun);
    NextLeaf  -> NextLeaf
  end.
```

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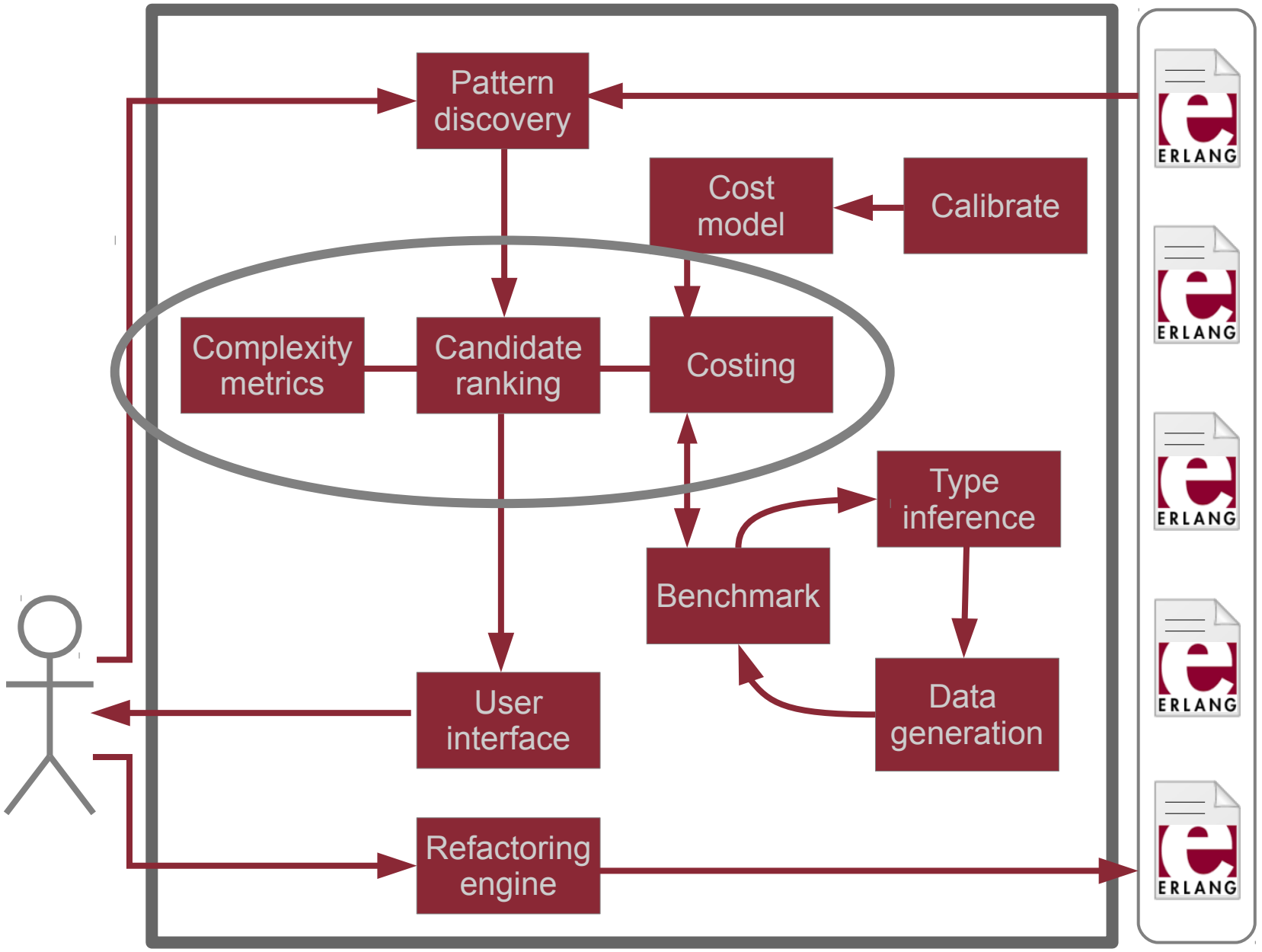

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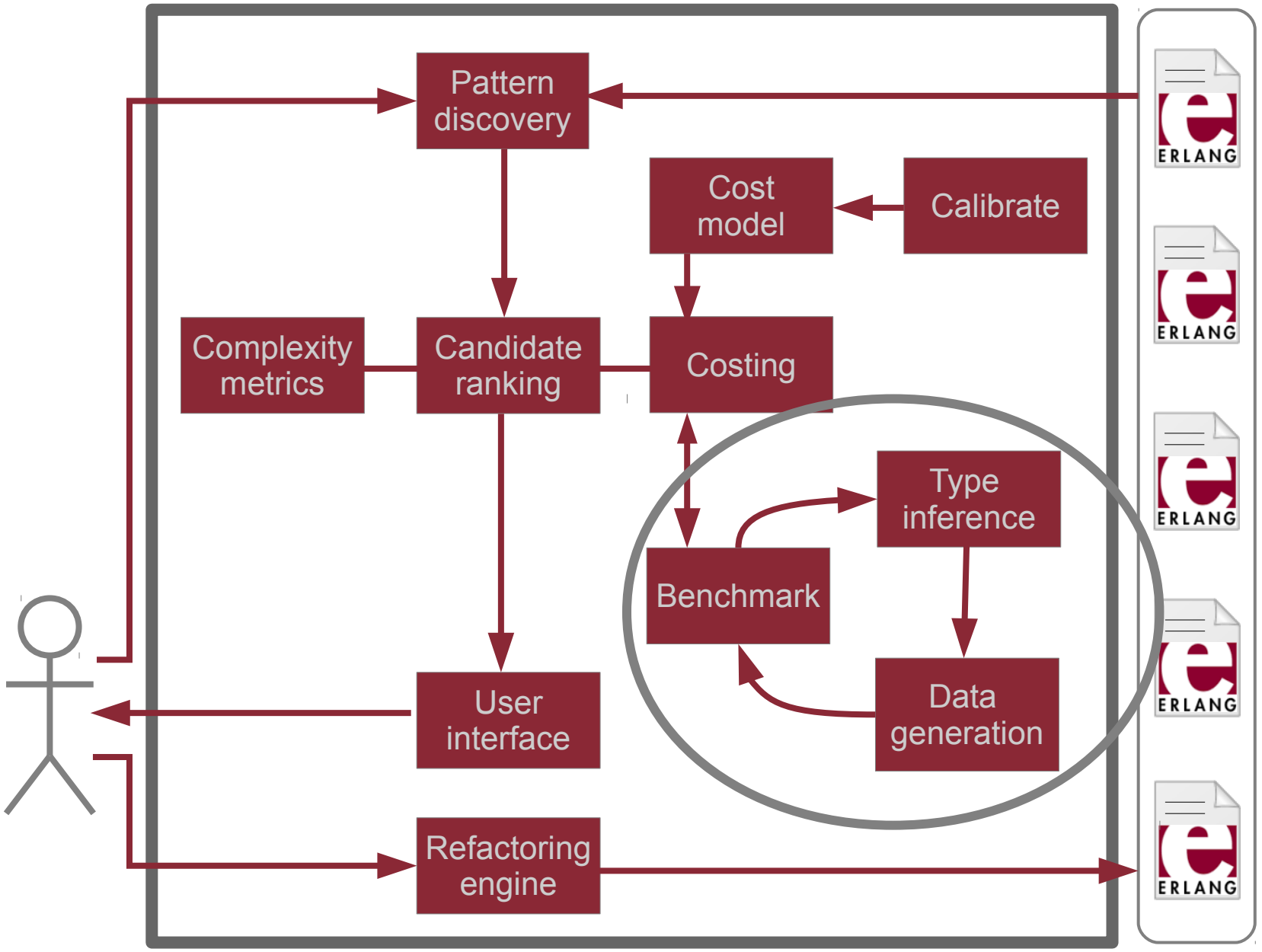

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Benchmarking

- Split up pattern candidates into components
- Determine free variables (inputs)
- Assemble a new module
  - Components turned into functions
  - Instrumented with time measurements
- Load module
- Generate random input and profile
- Make statistics

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Random input?

- Not always meaningful...
- ... but easy to automate!

- Find out the type of free variables (TypEr)
- QuickCheck generates values by type

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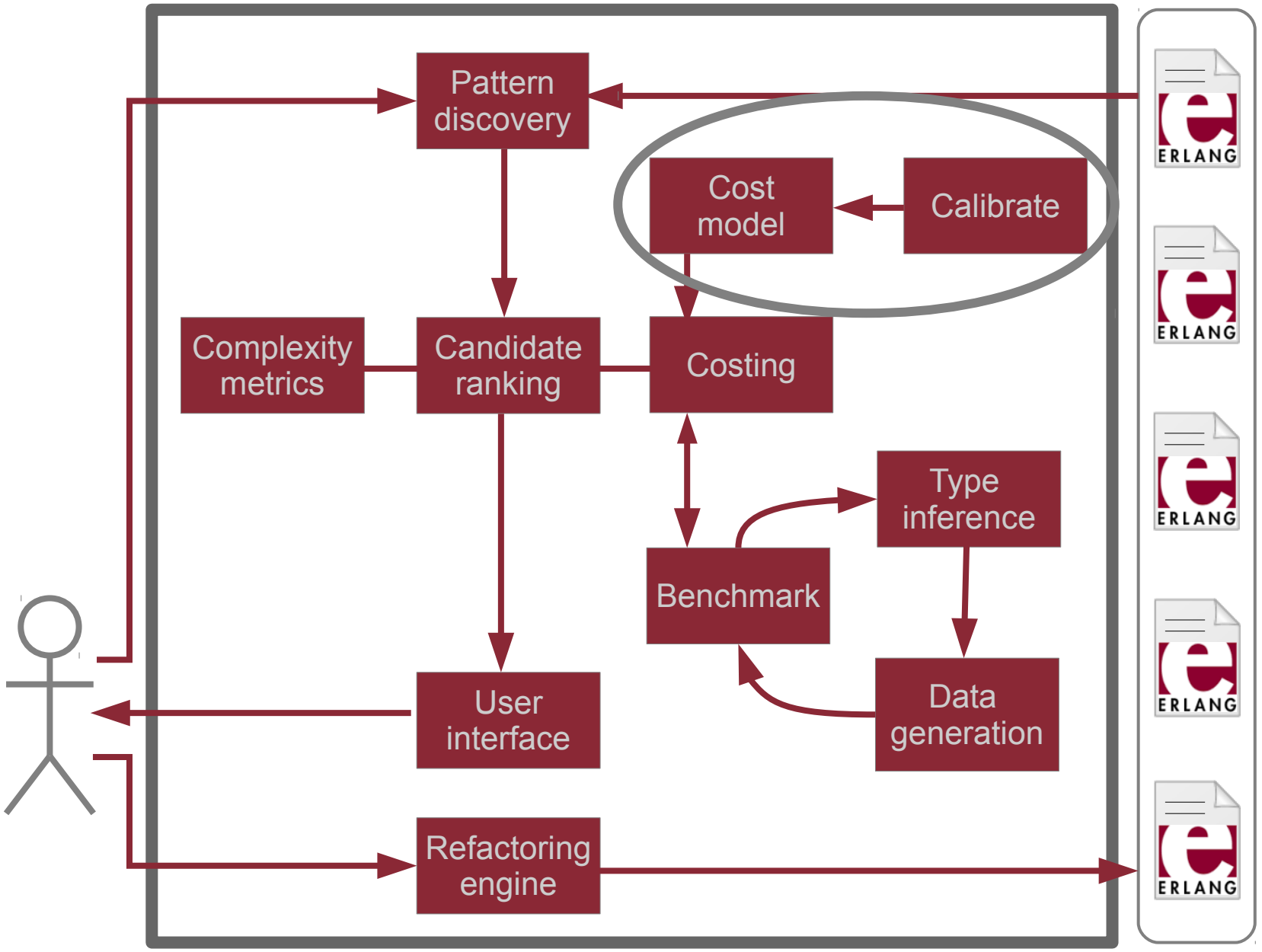

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Cost model

- Approximation
- E.g. for farm:

$$T_{farm} := T_{work} * \lceil L/min(N_p, N_w) \rceil + T_{spawn} * (N_w + 2) + T_{copy}(L) * 3 + T_{spawn} + T_{copy}(L) * 2$$

- Needs calibration!

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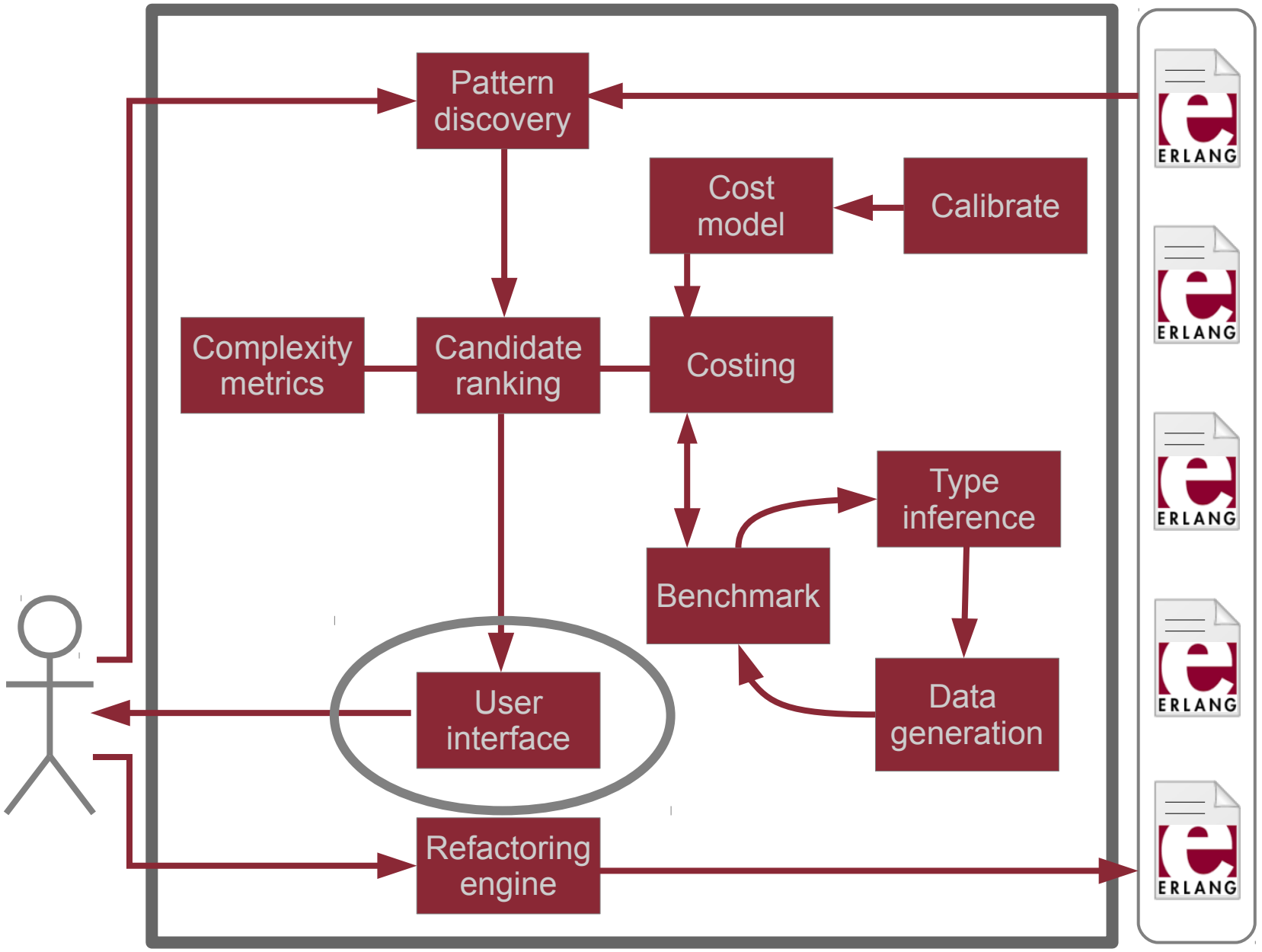

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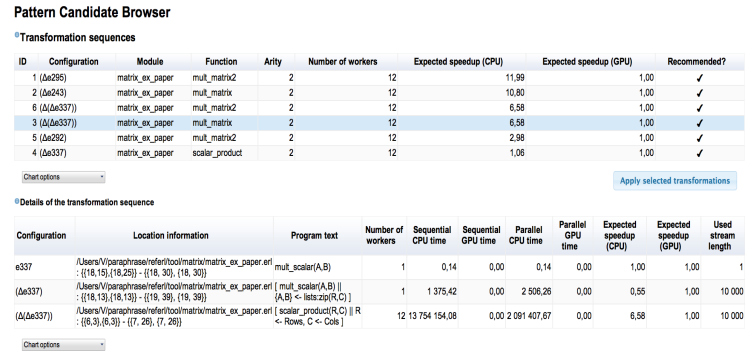
Pattern Candidate Browser

- After ranking pattern candidates
- Web-based interface
  - Information for decision making
  - Not too many details
- Services
  - Multiple users
  - Persistent results
  - Export XML, JSON, CSV, Erlang terms



Pattern Candidate Browser

Transformation sequences

ID	Configuration	Module	Function	Arity	Number of workers	Expected speedup (CPU)	Expected speedup (GPU)	Recommended?
1	(Δe295)	matrix_ex_paper	mult_matrix2	2	12	11,99	1,00	✓
2	(Δe243)	matrix_ex_paper	mult_matrix	2	12	10,80	1,00	✓
6	(Δ(Δe337))	matrix_ex_paper	mult_matrix2	2	12	6,58	1,00	✓
3	(Δ(Δe337))	matrix_ex_paper	mult_matrix	2	12	6,58	1,00	✓
5	(Δe292)	matrix_ex_paper	mult_matrix2	2	12	2,98	1,00	✓
4	(Δe337)	matrix_ex_paper	scalar_product	2	12	1,06	1,00	✓

Chart options

Apply selected transformations

Details of the transformation sequence

Configuration	Location information	Program text	Number of workers	Sequential CPU time	Sequential GPU time	Parallel CPU time	Parallel GPU time	Expected speedup (CPU)	Expected speedup (GPU)	Used stream length
e337	/Users/V/paraphrase/referi/tool/matrix/matrix_ex_paper.erl : {{18,15},{18,25}} - {{18, 30}, {18, 30}}	mult_scalar(A,B)	1	0,14	0,00	0,14	0,00	1,00	1,00	1
(Δe337)	/Users/V/paraphrase/referi/tool/matrix/matrix_ex_paper.erl : {{18,13},{18,13}} - {{19, 39}, {19, 39}}	[mult_scalar(A,B) || {A,B} <- lists:zip(R,C)]	1	1 375,42	0,00	2 506,26	0,00	0,55	1,00	10 000
(Δ(Δe337))	/Users/V/paraphrase/referi/tool/matrix/matrix_ex_paper.erl : {{6,3},{6,3}} - {{7, 26}, {7, 26}}	[scalar_product(R,C) || R <- Rows, C <- Cols]	12	13 754 154,08	0,00	2 091 407,67	0,00	6,58	1,00	10 000

Chart options

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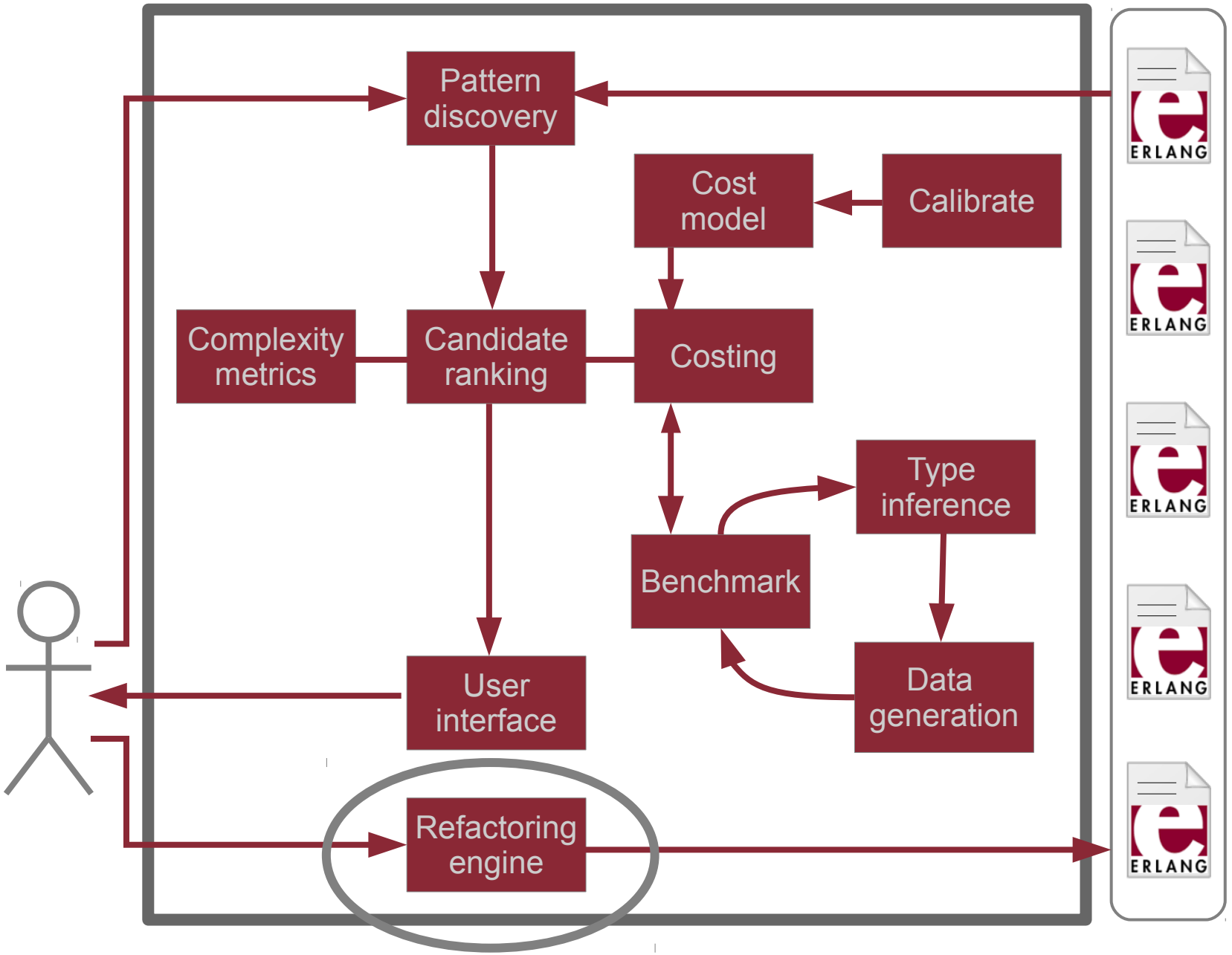

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Refactoring

- Program Shaping
- Introduction of Skeletons
- Cleanup Transformations

Either directly or after PC discovery

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Program shaping

- Restructures and tunes program to get it into appropriate shape for skeleton introduction
- Removal of:
  - Dependencies
  - Locks
  - Global State
  - Nestings
  - Copying

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Future work: more refactorings

```
sort( List ) -> sort(List,0).
sort( List,   _   ) when length(List) < 2 -> List;
sort( List, Level ) ->
  lists:append(
    [sort( Bucket, Level+1 ) || Bucket <- divide( List, Level )]
  ).
```

```
sort( List ) -> skel:do( [{ dc,
     fun({Lst,Level}) -> length(Lst) < 2 end,
     fun({Lst,Level}) -> Lst end,
     fun({Lst,Level}) ->
          [ {Bucket,Level+1} || Bucket <- divide(Lst, Level) ]
        end,
     fun lists:append/1
  }], {List,0}).
```

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Resources

ParaPhrase project (FP7 contract no. 288570)
http://paraphrase-ict.eu/

ParaPhrase @ ELTE
http://paraphrase-enlarged.elte.hu/

PaRTE docs & download:
http://pnyf.inf.elte.hu/trac/refactorerl/wiki/parte

CEFP 2015 instructions:
http://pnyf.inf.elte.hu/trac/refactorerl/wiki/parte/cefp

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Conclusions

- Pattern-based parallelism
- **Pa**raPhrase **R**efactoring **T**ool for **E**rlang

  Pattern discovery and refactoring

  Candidates prioritized,
  support for decision making
  - Finds many places to introduce parallelism
  - Supports candidate ranking
  - Works effectively with a smart programmer
  - Offers performance gains with small effort

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