OPENACS AND TCL/TK CONFERENCE 2026, JULY 17-18

- Andreas Kupries
- AKTIVE
  - AK Tcl Image Vector Extension
  - MIT/BSD Licensed
  - Inspired by VIPS
  - Mixes C and Tcl via Critcl

AK TCL IMAGE VECTOR EXTENSION

- Last year: Introduced by use, light on internals

AK TCL IMAGE VECTOR EXTENSION

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  - See [PDF] [ZIP] [WU Lecturecast] (Entire conference)

https://core.tcl-lang.org/akupries/aktive/doc/trunk/doc/presentations/eurotcl-2025-bologna.pdf

https://core.tcl-lang.org/akupries/aktive/doc/trunk/doc/presentations/eurotcl-2025-bologna.zip

https://learn.wu.ac.at/eurotcl2025/lecturecasts/753988258?m=delivery

https://learn.wu.ac.at/eurotcl2025/lecturecasts/?page=1

AK TCL IMAGE VECTOR EXTENSION

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- **Today**: A deeper look at the internals

AK TCL IMAGE VECTOR EXTENSION

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- **Today**: A deeper look at the internals
  - Demand-driven: Lazy construction

AK TCL IMAGE VECTOR EXTENSION

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  - Demand-driven: Lazy construction
    - Data structures (definition, run)

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    - Data structures (definition, run)
  - Horizontally Threaded Execution

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    - Thread coordination, ordered and not

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- Benchmarking & Performance

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  - Loop unrolling

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    - Thread coordination, ordered and not
- Benchmarking & Performance
  - Loop unrolling
  - (SIMD) Vectorization

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image creation builds **definition** structures

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image creation builds **definition** structures
  - Linear pipe

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image creation builds **definition** structures
  - Linear pipe
  - Tree

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image creation builds **definition** structures
  - Linear pipe
  - Tree
  - Directed acyclic graph

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image materialization builds **execution** structures

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image materialization builds **execution** structures
  - ... computes things

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image materialization builds **execution** structures
  - ... computes things
  - ... and tears the execution structures down again

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Image materialization builds **execution** structures
  - ... computes things
  - ... and tears the execution structures down again
  - **The definition structures stay**

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Examples of materializators

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Examples of materializators
  - Saving pixels to file, channel, memory, ...

AK TCL IMAGE VECTOR EXTENSION

LAZY CONSTRUCTION

- Examples of materializators
  - Saving pixels to file, channel, memory, ...
  - Computing whole-image statistics

AK TCL IMAGE VECTOR EXTENSION

PREFACE: INSPECTION


```
aktive format as d2         $image
aktive format as markdown   $image
aktive format as tclscript $image
```

AK TCL IMAGE VECTOR EXTENSION

PREFACE: INSPECTION


```
aktive format as d2         $image
aktive format as markdown   $image
aktive format as tclscript $image
```

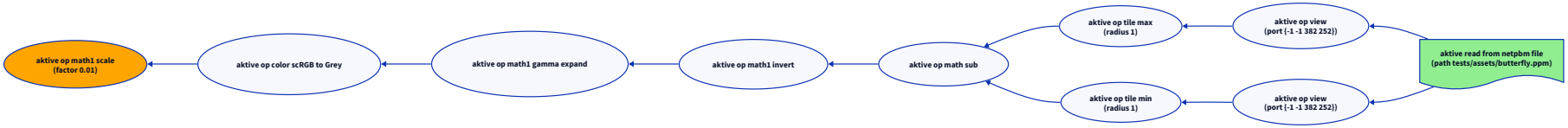
```
set file1 [aktive read from netpbm file path ...];# FO(2): tmp2,tmp
set tmp2 [aktive op view $file1 port {-1 -1 382 252}]
set tmp3 [aktive op tile max $tmp2 radius 1]
set tmp4 [aktive op view $file1 port {-1 -1 382 252}]
set tmp5 [aktive op tile min $tmp4 radius 1]
set tmp6 [aktive op math sub $tmp3 $tmp5]
set tmp7 [aktive op math1 invert $tmp6]
set tmp8 [aktive op math1 gamma expand $tmp7]
set tmp9 [aktive op color scRGB to Grey $tmp8]
set result [aktive op math1 scale $tmp9 factor 0.01]
```

AK TCL IMAGE VECTOR EXTENSION

PREFACE: INSPECTION


```
aktive format as d2          $image
aktive format as markdown    $image
aktive format as tclscript $image
```

Charcoal effect

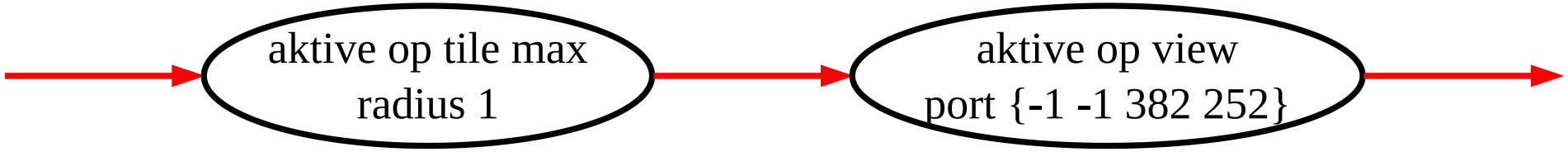


full size (assets/charcoal.svg)

AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

Shoutout: Pikchr @ https://pikchr.org



AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

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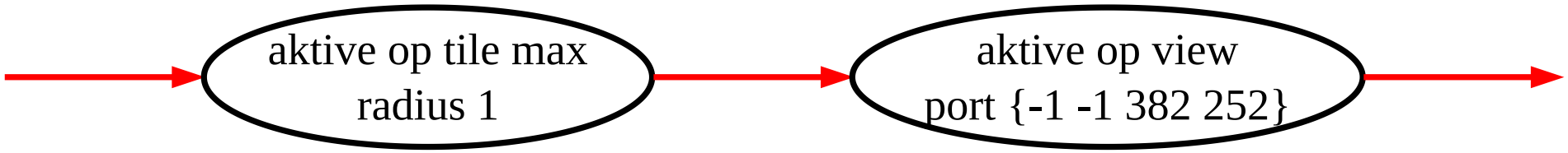
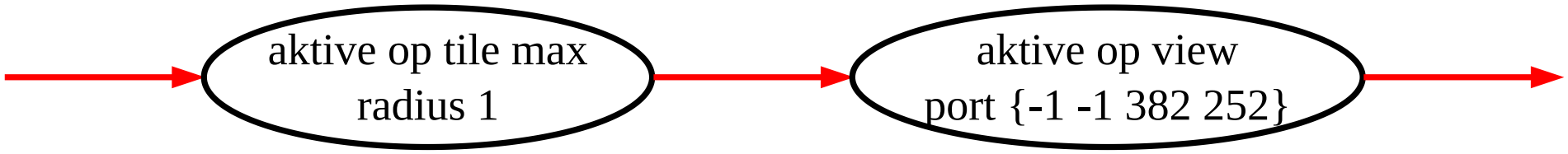


- type (function vectors, parameter defs)
- parameters
- srcs
- domain (geometry)
- state

AK TCL IMAGE VECTOR EXTENSION

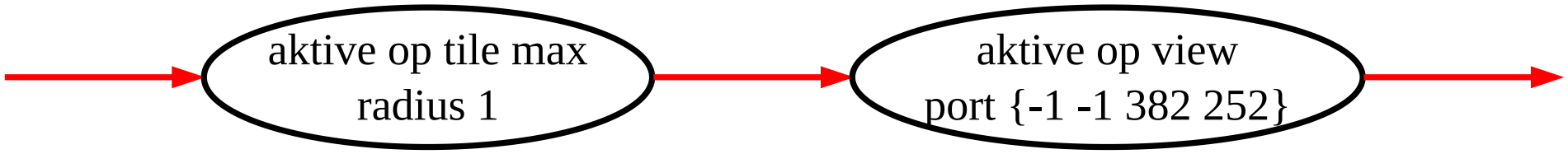
DEFINITION STRUCTURES



- type (function vectors, parameter defs)
- content (parameters, srcs, domain, state)

AK TCL IMAGE VECTOR EXTENSION

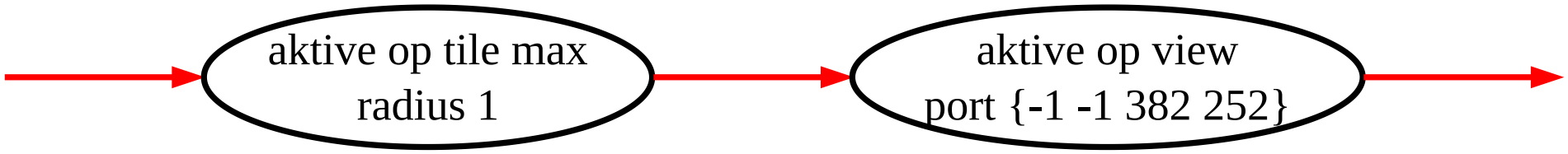
DEFINITION STRUCTURES



- type (function vectors, parameter defs)
- content (parameters, srcs, domain, state)
- metadata

AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

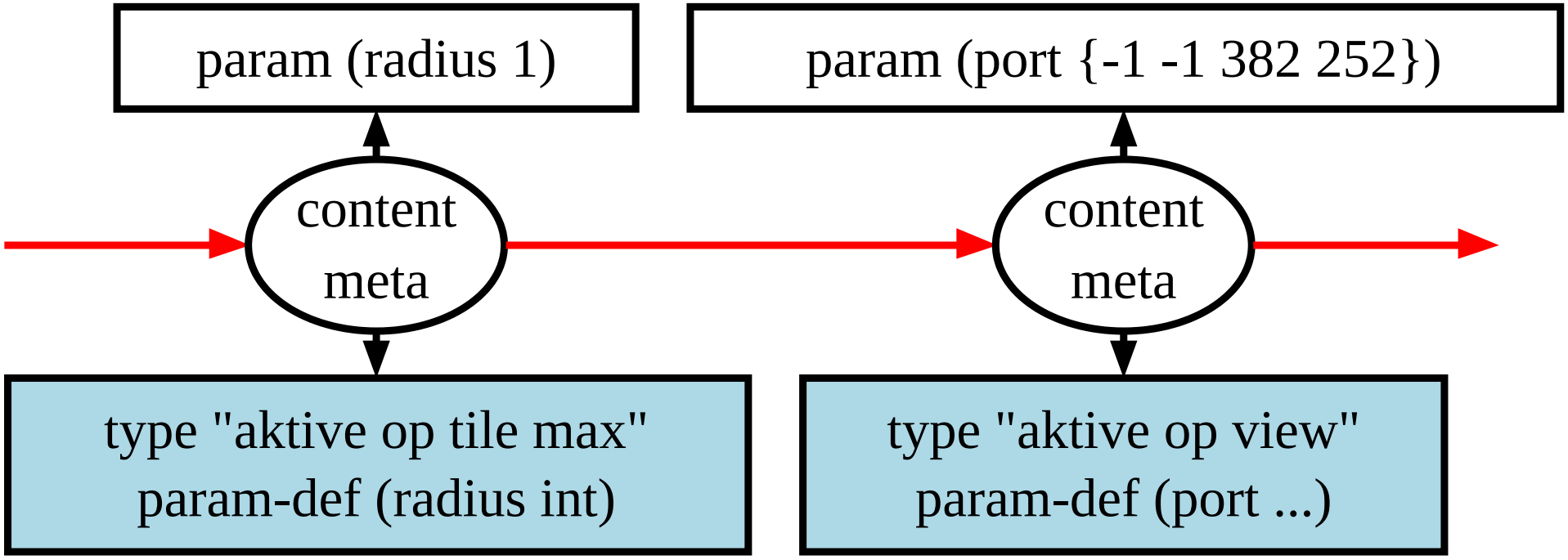


- type (function vectors, parameter defs)
- content (parameters, srcs, domain, state)
- metadata
- refcount

AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

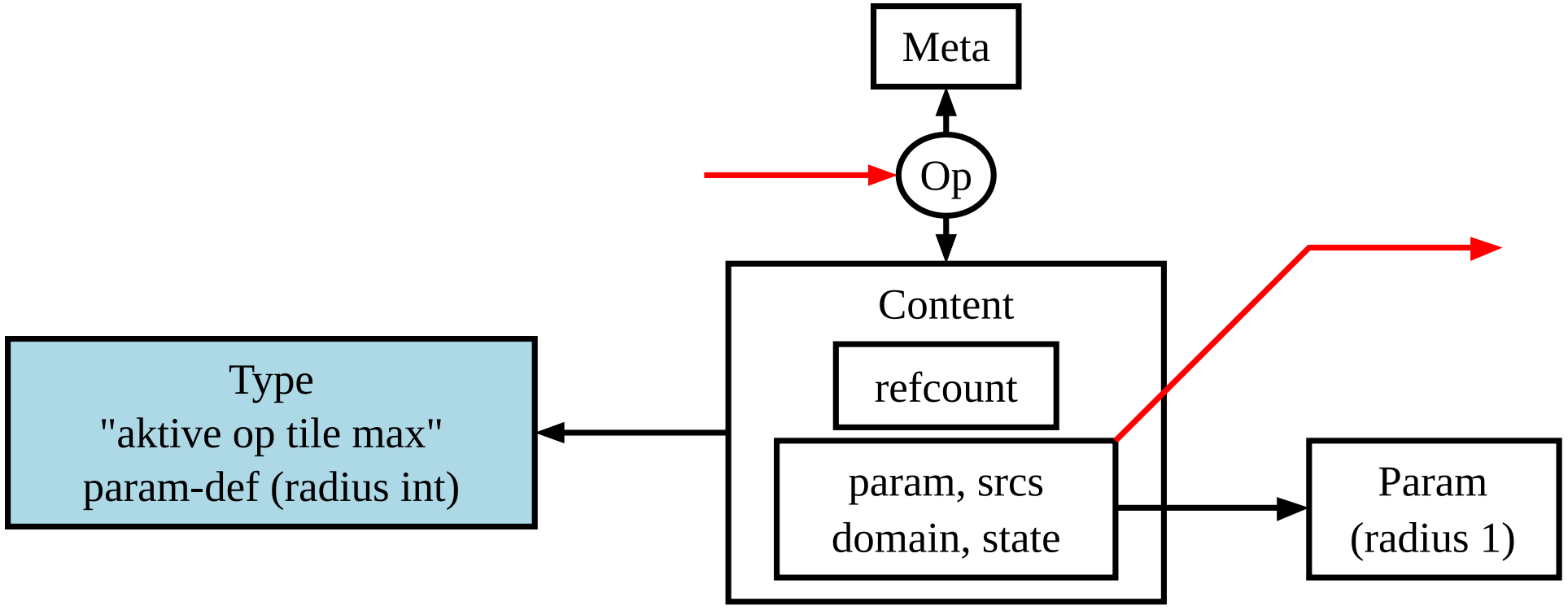
Types and Parameters



AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

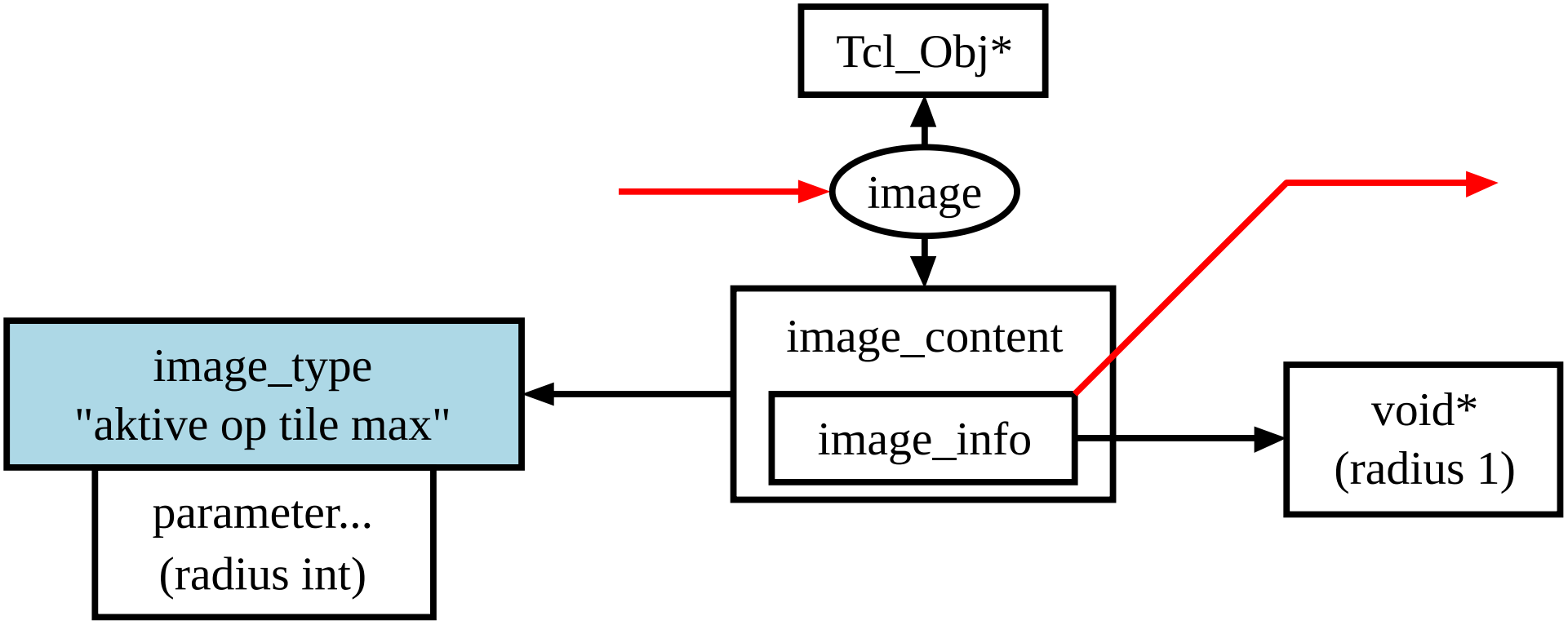
Content and Meta



AK TCL IMAGE VECTOR EXTENSION

DEFINITION STRUCTURES

C Types



AK TCL IMAGE VECTOR EXTENSION

RUNTIME STRUCTURES

- (runtime) state
- (runtime) srcs
- result buffer
- image

AK TCL IMAGE VECTOR EXTENSION

RUNTIME STRUCTURES

- (runtime) state
- (runtime) srcs
- result buffer
- image
  - param
  - type
  - domain
  - state

AK TCL IMAGE VECTOR EXTENSION

RUNTIME STRUCTURES

- **region**: result buffer, image, type
- **region_info**: runtime state, runtime srcs, param, domain, def state

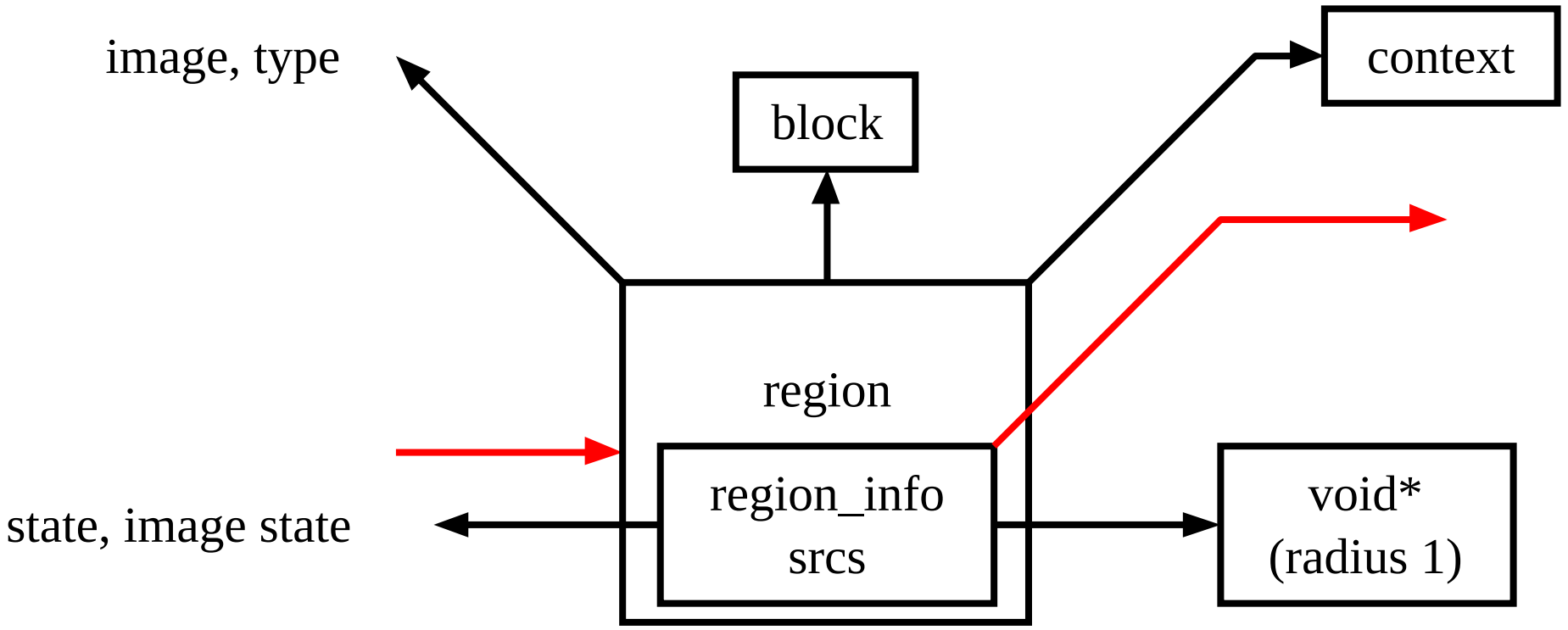
AK TCL IMAGE VECTOR EXTENSION

RUNTIME STRUCTURES

- **region**: result buffer, image, type
- **region_info**: runtime state, runtime srcs, param, domain, def state
- context

AK TCL IMAGE VECTOR EXTENSION

RUNTIME STRUCTURES



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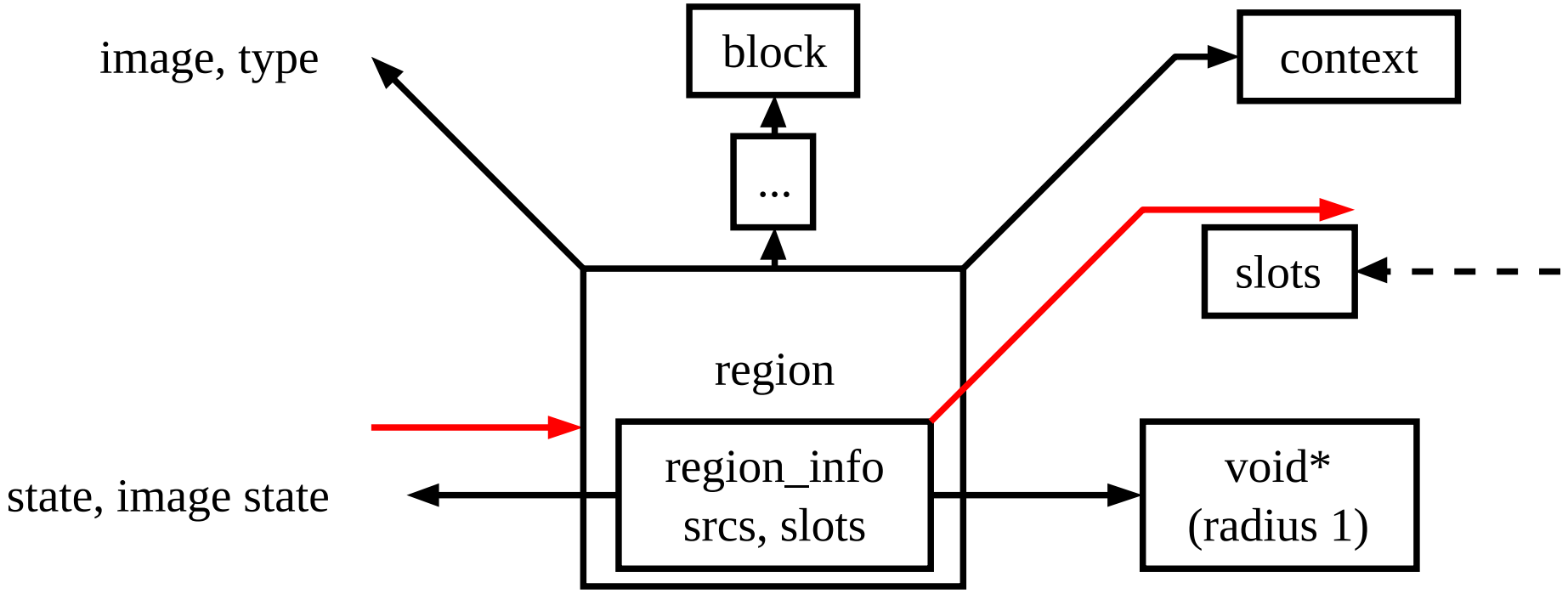
RUNTIME STRUCTURES



AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks
- Process tasks

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks
- Process tasks
- Collect results

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks
- Collect results

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
- Collect results

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
- Collect results --- **Completer**

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
  - Here are the runtime structures
- Collect results --- **Completer**

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
  - Here are the runtime structures
- Collect results --- **Completer**

Coordination ?

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
  - Here are the runtime structures
- Collect results --- **Completer**

Coordination ?

- Unordered

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

- Generate tasks --- **Maker**
- Process tasks --- **Workers**
  - Here are the runtime structures
- Collect results --- **Completer**

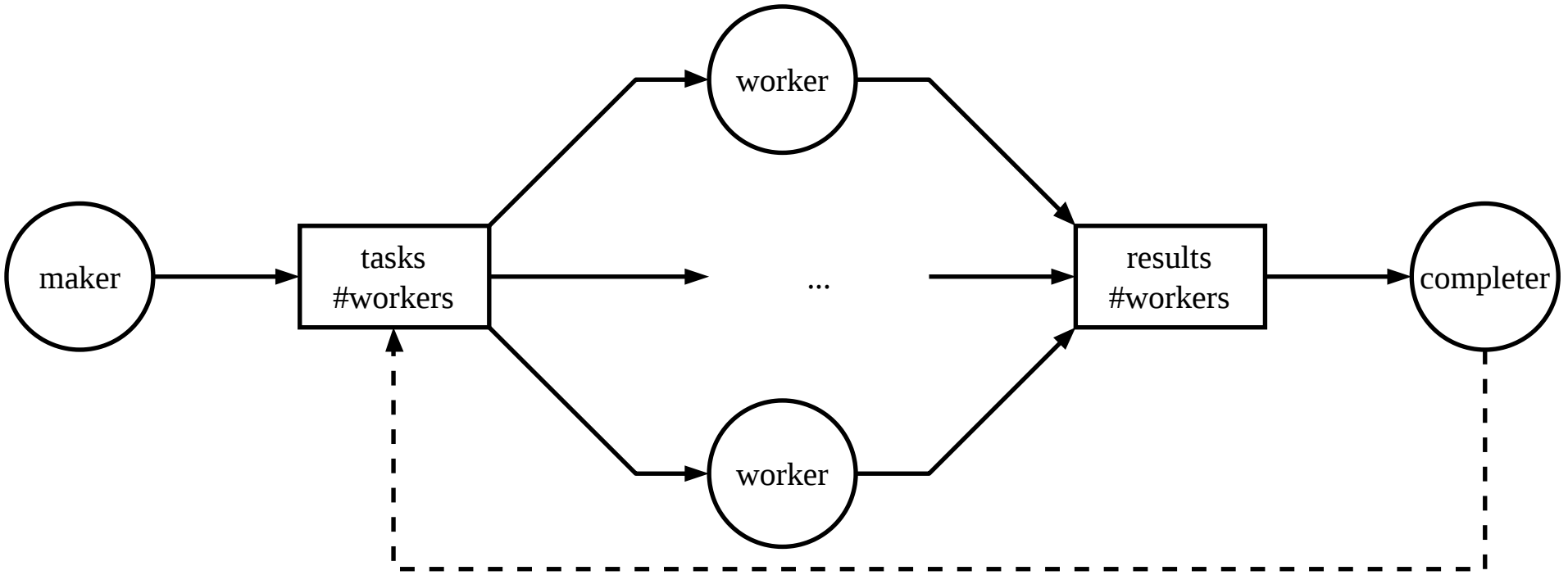
Coordination ?

- Unordered
- Sequential

AK TCL IMAGE VECTOR EXTENSION

HORIZONTALLY THREADED EXECUTION

Unordered



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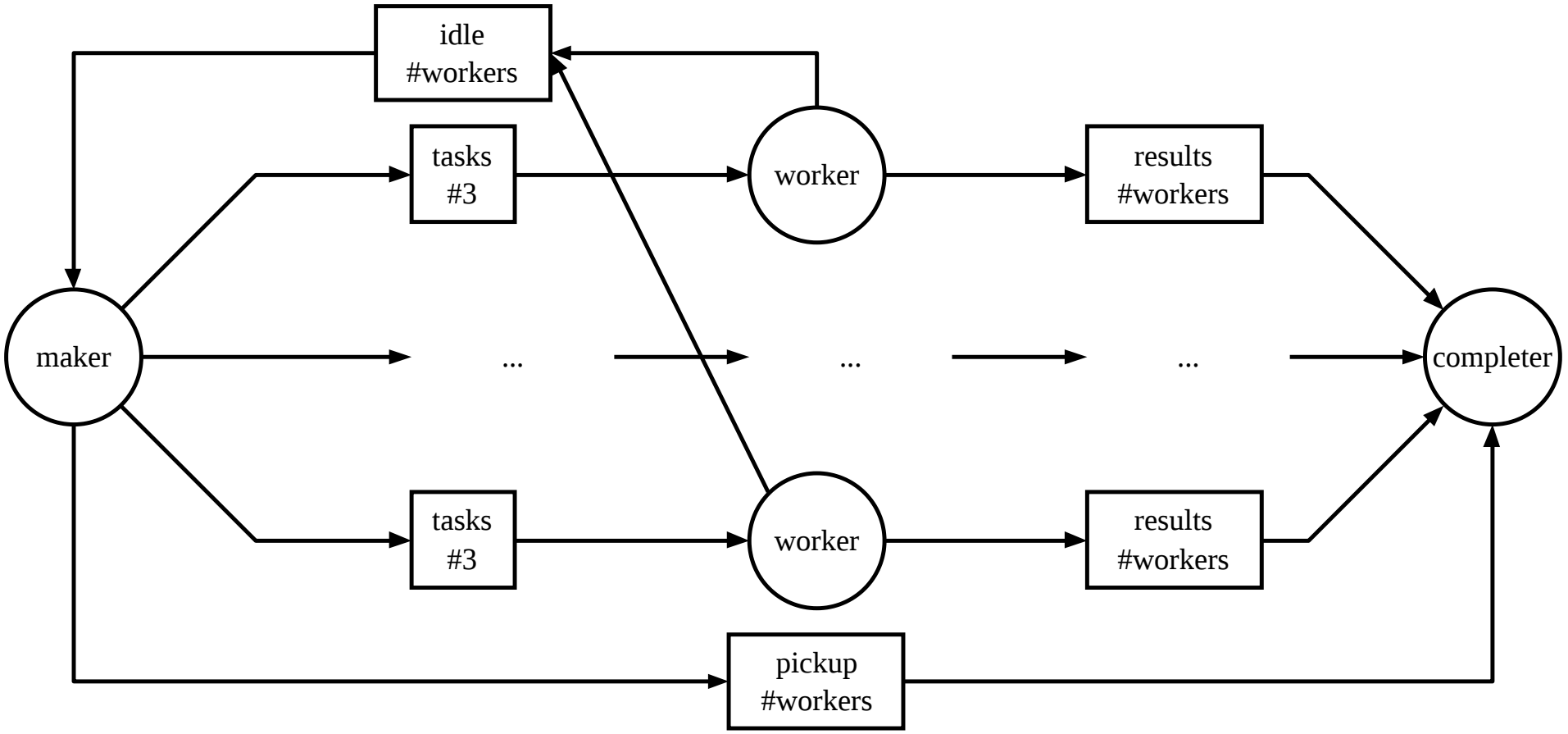
HORIZONTALLY THREADED EXECUTION

Sequential


idle
#workers
tasks
#3
worker
results
#workers
maker
...
...
...
completer
tasks
#3
worker
results
#workers
pickup
#workers

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE


```
op-bench {
    aktive image from value // width %W height %H depth 1 value 0.5
}
```

AK TCL IMAGE VECTOR EXTENSION

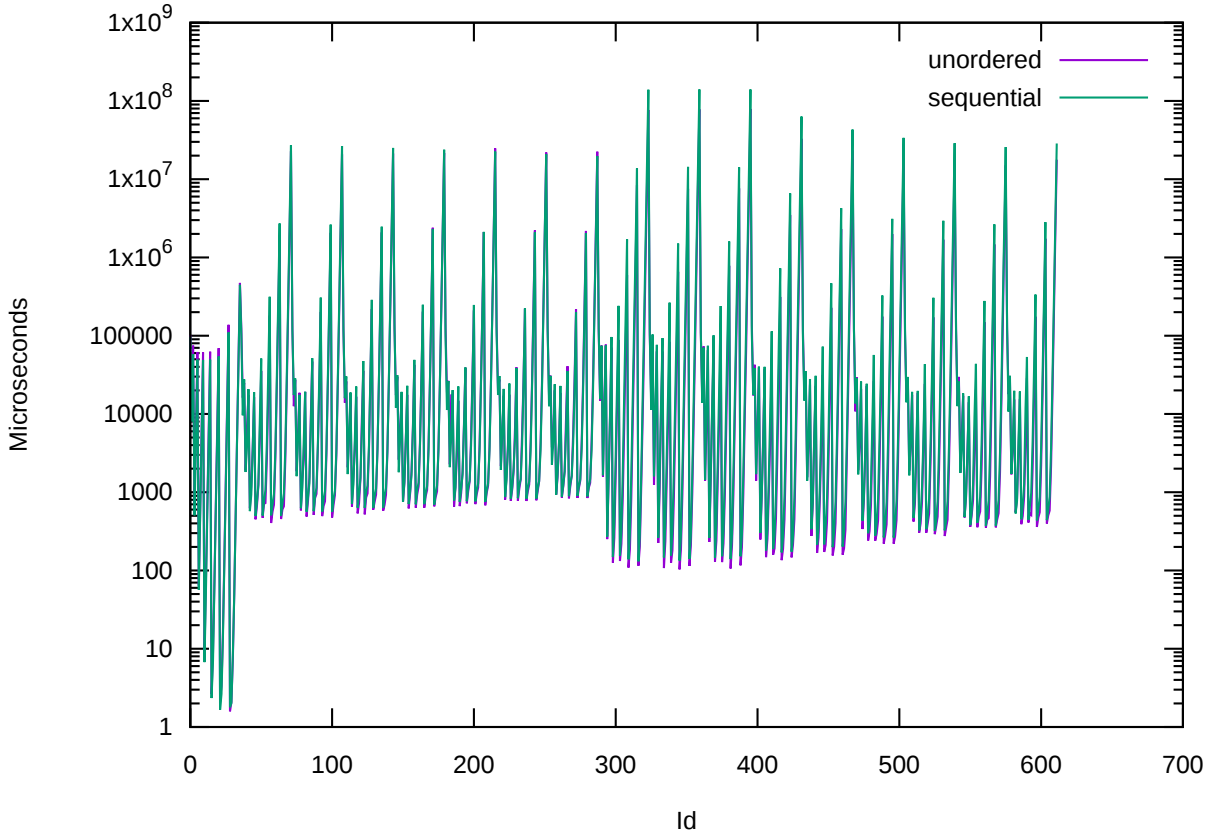
BENCHMARKING & PERFORMANCE


```
    foreach sink {
        null
        null-s
    } {
        # varying concurrency ... unthreaded, ...
        #                     ... threads up to num cpu cores, ...
        #                     ... then overcommitted cpu ...
        foreach cores {
            -1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
        } {
            # varying sizes ... small to large
            foreach size {
                1 10 100 1000 10000 100000 1000000 10000000
            } { ;#       1K   10K   100K   1M      10M
                # varying shapes of the same size ... tall to wide
                for { set h $size ; set w 1 } { $h > 0 } {
                    set w [expr {$w*10}] ; set h [expr {$h/10}]
                } { ...
```

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

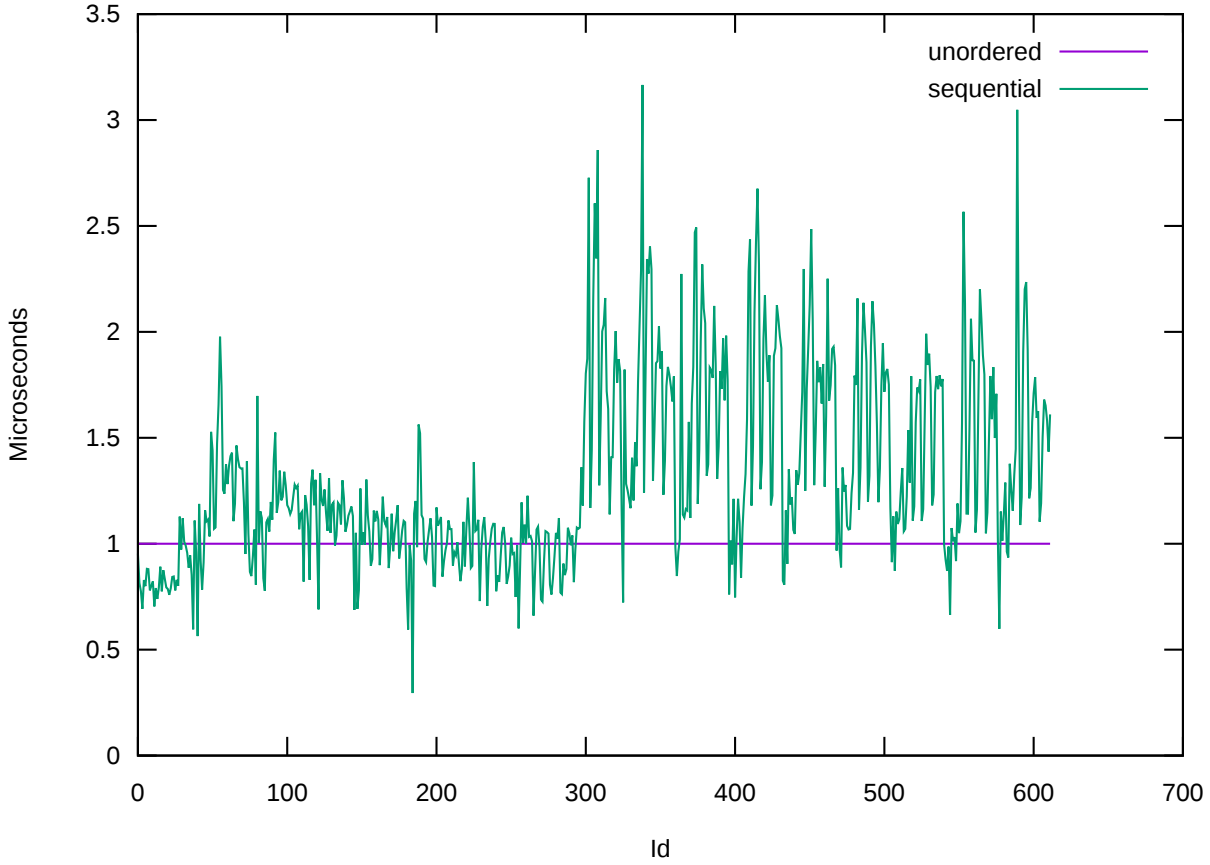
Unordered vs. Sequential


1x10^9
1x10^8
1x10^7
1x10^6
100000
10000
1000
100
10
1
Microseconds
0
100
200
300
400
500
600
700
Id
unordered
sequential

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

Unordered vs. Sequential


unordered
sequential
Microseconds
Id
0
0.5
1
1.5
2
2.5
3
3.5
0
100
200
300
400
500
600
700

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Currently: Performance through threading

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Currently: Performance through threading
- Can we gain more ? How ?

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Currently: Performance through threading
- Can we gain more ? How ?
- Make the workers themselves faster!

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!
  - Idea 1: Loop unrolling

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BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!
  - Idea 1: Loop unrolling
    - Out of Order Superscalar

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BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!
  - Idea 1: Loop unrolling
    - Out of Order Superscalar
  - Idea 2: Vectorization (SIMD)

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!
  - Idea 1: Loop unrolling
    - Out of Order Superscalar
  - Idea 2: Vectorization (SIMD)
    - x86 SSE*, AVX*, Arm NEON, SVE, RISC-V "V"

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

- Make the workers themselves faster!
  - Idea 1: Loop unrolling
    - Out of Order Superscalar
  - Idea 2: Vectorization (SIMD)
    - x86 SSE*, AVX*, Arm NEON, SVE, RISC-V "V"
    - Google Highway (Portable, Length-Agnostic) @ https://github.com/google/highway

AK TCL IMAGE VECTOR EXTENSION

Function specification


```
set unary0 {
    acos            { scalar { v = acos  (v);     } }
    [...]
}

set unary1 {
    [...]
    shift  {
        scalar  { v = v + a;       }
        highway { v = Add (v, a); }
    }
    [...]
}
```

AK TCL IMAGE VECTOR EXTENSION

Templating


```
set u4_unary0_vdecl {
    extern void aktive_vector4_unary_@name@ (
        double* d, double* s, aktive_uint n);
}
set u4_unary0_vdef {
    void aktive_vector4_unary_@name@ (double* d, double* s, aktive_uint n) {
        // 4-unroll
        for (; n > 3; n -= 4, d += 4, s += 4) {
            double v0 = s[0]; // v1, v2, v3 = s[1,2,3]
#define v v0 // ... v1 v2 v3
            @opcode@
#undef  v
            d[0] = v0; // d[1,2,3] = v1, v2, v3
        }
        // 2-unroll,
        for (; n > 1; n -= 2, d += 2, s += 2) { ... }
        // remainder
        for (; n > 0; n--, d++, s++) { ... }
    }
}
```

AK TCL IMAGE VECTOR EXTENSION

Templating


```
set u1_unary0_hdecl {
    void aktive_highway1_unary_@name@ (
        double* d, double* s, aktive_uint n);}
set u1_unary0_hdef  {
    HWY_ATTR void aktive_highway1_unary_@name@ (
        double* d, double* s, aktive_uint n) {
        const int32_t N = Lanes(f64);
        @decls@
        if (n < N) {    // not a full block - do a masked partial op
            auto mask = FirstN(f64, n);
            auto v    = MaskedLoad(mask, f64, s);
            @opcode@
            BlendedStore (v, mask, f64, d);         return;
        }
        aktive_uint k, border = n - N;  // lane-sized blocks
        for (k = 0; k < n; k += N) {
            aktive_uint at = HWY_MIN (k, border);
            auto v = LoadU (f64, s + at);
            @opcode@
            StoreU (v, f64, d + at);
        }
    }
}
```

AK TCL IMAGE VECTOR EXTENSION

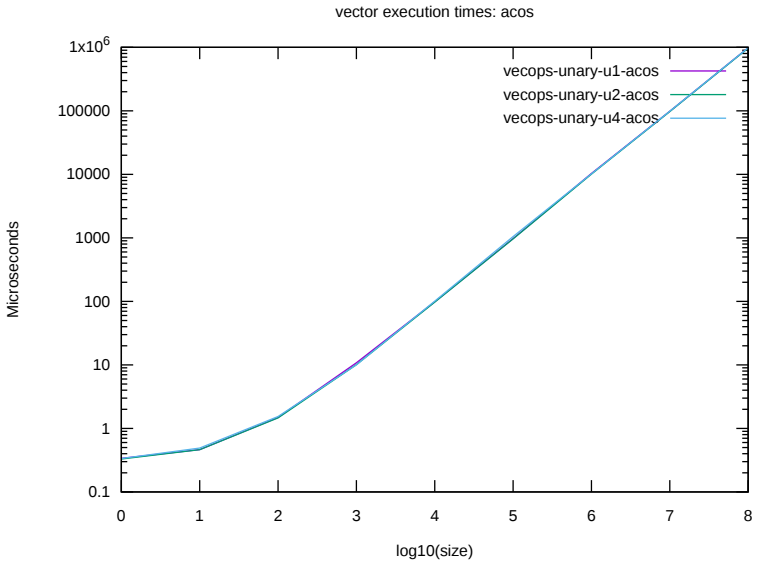
Templating

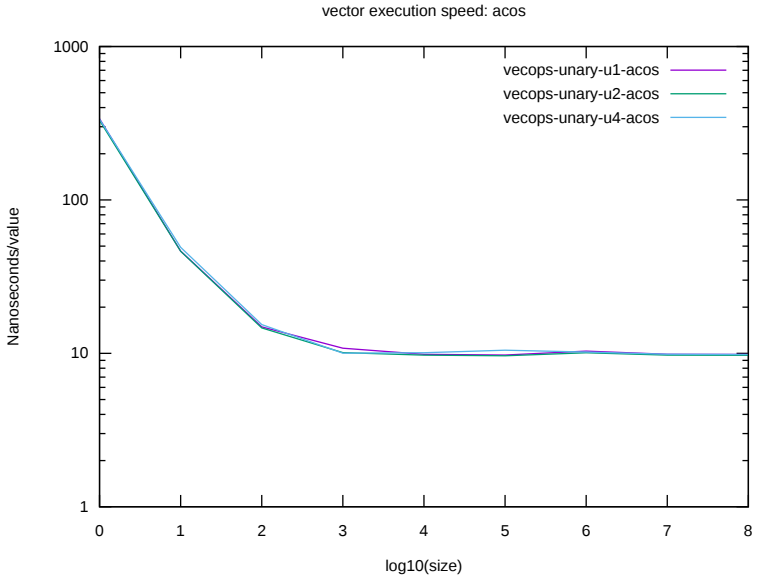

```
set u1_unary0_hdecl {
    void aktive_highway1_unary_@name@ (
        double* d, double* s, aktive_uint n);}
set u1_unary0_hdef  {
    HWY_ATTR void aktive_highway1_unary_@name@ (
        double* d, double* s, aktive_uint n) {
        const int32_t N = Lanes(f64);
        @decls@
        if (n < N) {    // not a full block - do a masked partial op
            auto mask = FirstN(f64, n);
            auto v    = MaskedLoad(mask, f64, s);
            @opcode@
            BlendedStore (v, mask, f64, d);         return;
        }
        aktive_uint k, border = n - N;  // lane-sized blocks
        for (k = 0; k < n; k += N) {
            aktive_uint at = HWY_MIN (k, border);
            auto v = LoadU (f64, s + at);
            @opcode@
            StoreU (v, f64, d + at);
        }
    }
}
```

AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

Loop Unrolling (1x, 2x, 4x) -- **acos**

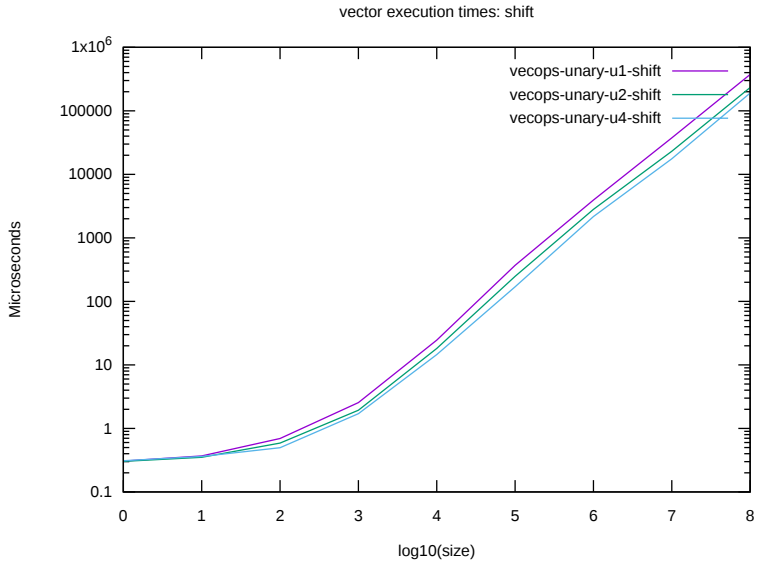


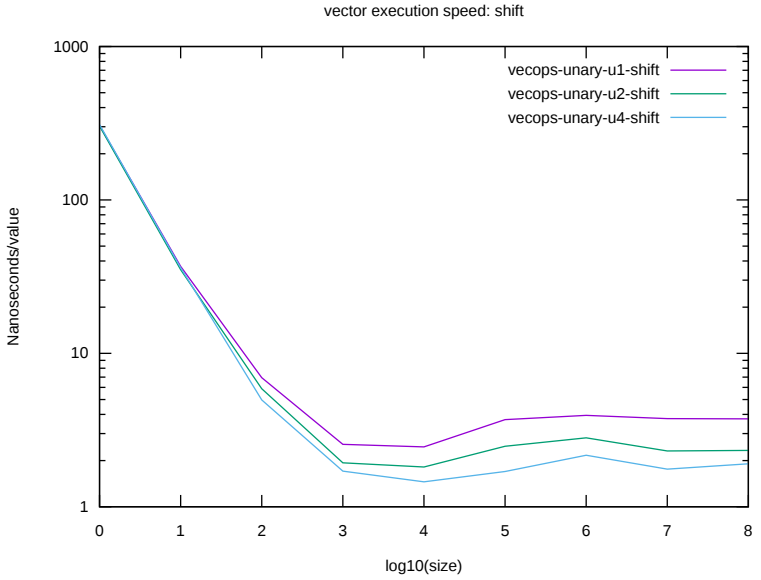


AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

Loop Unrolling (1x, 2x, 4x) -- **shift**

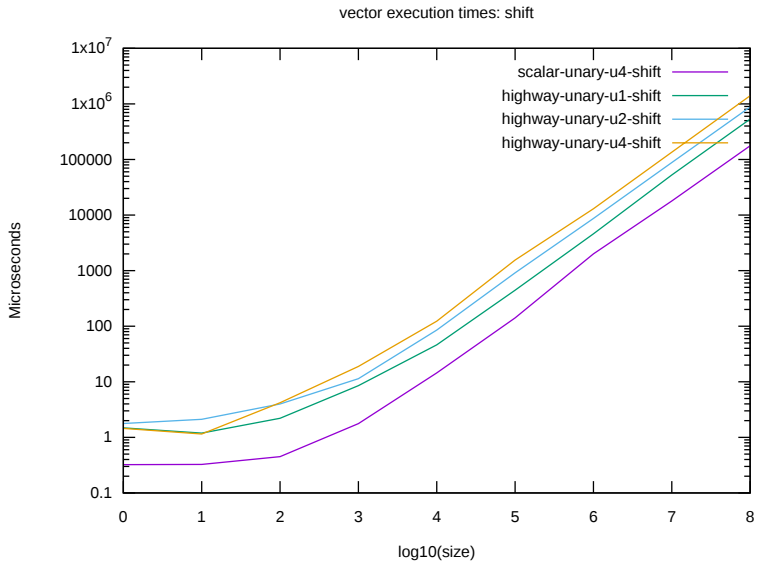


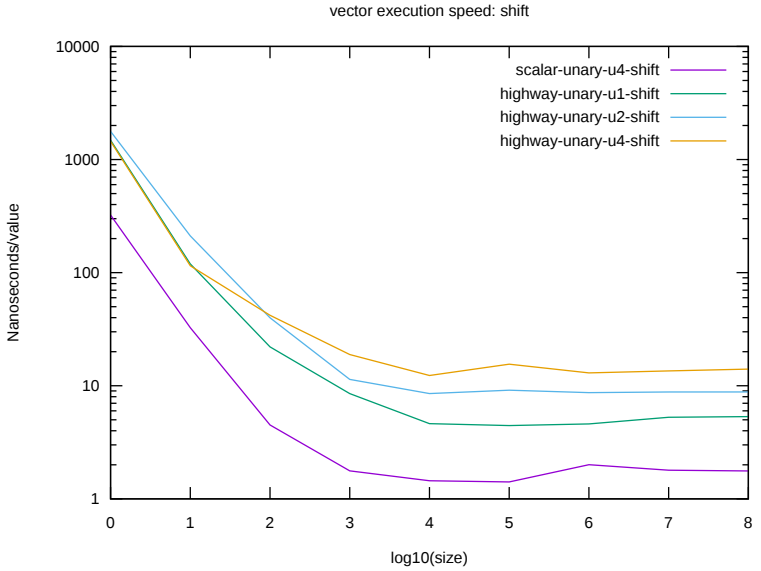


AK TCL IMAGE VECTOR EXTENSION

BENCHMARKING & PERFORMANCE

Loop Unrolling 4x vs Highway -- **shift**





https://core.tcl-lang.org/akupries/aktive/doc/highway-simd-experiment/bench/plots/simd/README.md

https://core.tcl-lang.org/akupries/aktive/timeline?r=highway-simd-experiment

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BENCHMARKING & PERFORMANCE

Benchmarks

https://core.tcl-lang.org/akupries/aktive/doc/trunk/bench/plots/README.md

SIMD Benchmarks

https://core.tcl-lang.org/akupries/aktive/doc/highway-simd-experiment/bench/plots/README.md

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- Questions ? ...