

The LEAPS Algorithms¹

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Abstract

LEAPS is a state-of-the-art production system compiler that produces the fastest sequential executables of OPS5 rule sets. The performance of LEAPS is due to its reliance on complex data structures and search algorithms to speed rule processing. In this paper, we explain the LEAPS algorithms in terms of the programming abstractions of the P2 data structure compiler.

1 Introduction

OPS5 is a forward-chaining expert system [McD78, For81]. LEAPS (*Lazy Evaluation Algorithm for Production Systems*) is a state-of-the-art production system compiler for OPS5 rule sets [Mir90].² Experimental results have shown that LEAPS produces the fastest sequential executables of OPS5 rule sets; execution times can be over two orders of magnitude faster than OPS5 interpreters. This phenomenal speedup is due to the reliance of LEAPS on complex data structures and search algorithms to greatly increase rule firing rates. It is well-known that LEAPS data structures and algorithms are difficult to comprehend; this is due, in part, to the inability of relational database concepts (i.e., relations and select-project-join operators) to capture critical lazy-evaluation features of LEAPS algorithms.

In this paper, we explain the LEAPS algorithms in terms of the container-cursor programming abstractions of the P2 data structure compiler [Sir93, Bat93]. Our specifications of the LEAPS algorithms were used as the basis for the RL (Reengineered-LEAPS) project [Bat94] and have been validated through implementation. Thus, this paper describes a reimplementaion of LEAPS using P2. We begin by reviewing relevant P2 abstractions.

2 P2 Programming Abstractions

There are four programming abstractions that are offered by P2 that are critical to the understanding of LEAPS algorithms: cursors, containers, composite cursors, and type expressions. Each concept is explained in the following sections.

2.1 Cursors and Containers

Many common data structures—arrays, binary trees, ordered lists—implement the container abstraction. A *container* is a sequence of elements, where all the elements are instances of a single data type. Elements can only be referenced and updated by a run-time object called a *cursor* (see Figure 1).

1. This research was supported in part by the Applied Research Laboratories at the University of Texas and Schlumberger.

2. Actually, OPS5c version 5 is the name of the production system compiler; LEAPS is the name of the algorithms. We will use OPS5c/LEAPS and LEAPS interchangeably in this paper.

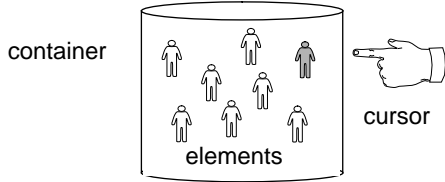


Figure 1. Basic P2 Abstractions

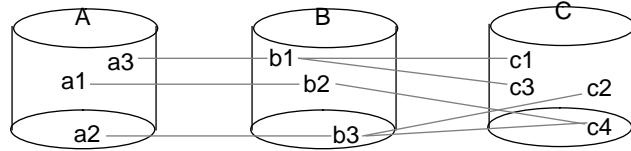


Figure 2. A Multicontainer Relationship

The P2 programming language is a superset of C. P2 introduces statements for cursor and container declarations, along with special operations on cursors and containers. An abbreviated declaration of a container of **EMPLOYEE_TYPE** instances is shown below, along with declarations of a cursor (**all_employees**) that references all elements of this container and another cursor (**selected_employees**) that references only those elements whose **deptno** field has the value 10:

```
// Declaration of the employee container.
container <EMPLOYEE_TYPE> employee;

// Cursor that references all elements in the employee container.
cursor <employee> all_employees;

// Cursor that references selected elements of employee container.
cursor <employee> where "$.deptno == 10" selected_employees;
```

P2 offers an (extensible) set of container and cursor operations. For example, the **foreach** construct is used to iterate over qualified elements of a container. The **foreach** loop below prints the names of selected employees:

```
// For each element whose deptno field has the value 10.
foreach( selected_employees )
{
  // Print the employee name.
  printf( "%s\n", selected_employees.name );
}
```

2.2 Composite Cursors

Complex data structures consist of multiple containers whose elements are interconnected by pointers. A *relationship* among containers C_1, C_2, \dots, C_n is a set of n-tuples $\langle e_1, e_2, \dots, e_n \rangle$ where element e_i is a member of container C_i . Figure 2 depicts a relationship for containers **A**, **B**, and **C** whose 3-tuples are:

$$\{(a3, b1, c1), (a3, b1, c3), (a1, b2, c4), (a2, b3, c2), (a2, b3, c4)\}$$

A *composite cursor* enumerates the n-tuples of a relationship. More specifically, a composite cursor k is an n-tuple of cursors, one cursor per container of a relationship. A particular n-tuple $\langle e_1, e_2, \dots, e_n \rangle$ of a relationship is encoded by having the i th cursor of k positioned on element e_i . By advancing k , successive n-tuples of a relationship are retrieved.

As an example, a composite cursor **c** that joins elements of the **department** and **employee** containers that share the same value of the **deptno** field is specified in P2 as:³

3. Note that predicates in P2 are expressed by strings. Field **F** of the element referenced by a cursor is denoted "\$.**F**". A cursor over container with alias **x** is denoted "\$**x**".

```
compcurs < d department, e employee > where "$d.deptno == $e.deptno" c;
```

d and **e** are aliases for container names. (As we will see in Section 3.2, aliases are useful for expressing the joins of containers with themselves in an unambiguous way). The **foreach** loop below prints (**employee** name, **department** name) pairs. Readers may recognize this loop as a natural join between **department** and **employee** containers:

```
foreach( c )
{ printf( "%s %s\n", c.e.name, c.d.name ); }
```

Occasionally, it is useful to retrieve only n-tuples of a relationship that involve specific objects. Suppose we are interested only in the 3-tuples of Figure 2 that involve element **b3** of container **B** (i.e., tuples (**a2,b3,c2**) and (**a2,b3,c4**)). Such a retrieval is called *seeding* a relationship with **b3**. Seedings are expressed in P2 by augmenting the **compcurs** declaration with a **given** clause (which lists aliases of all containers that are to be seeded). Prior to a **foreach**, the **given** cursors must be positioned on the seeding elements. The above example with **b3** would be expressed by the following **compcurs** declaration and **foreach** code fragment:

```
// Declare seeded_composite_cursor seeded by b.
compcurs < a A, b B, c C > given < b > seeded_composite_cursor;

// Position seeded_composite_cursor.b
position( seeded_composite_cursor.b, address_of(b3) );

// Iterate over seeded tuples.
foreach( seeded_composite_cursor )
{ ... }
```

Updating elements within a **foreach** loop is possible. Such updates may affect the n-tuples that are retrieved by a composite cursor. Again consider the example of composite cursor **c** which returns pairs of related **department** and **employee** elements. The **foreach** of Figure 3a deletes the **department** element for each retrieved ordered pair.

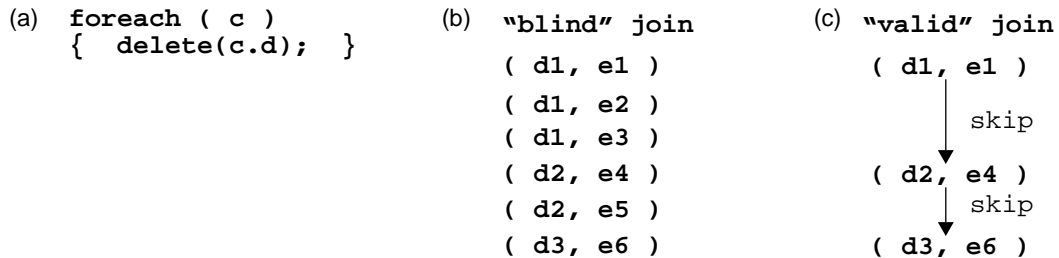


Figure 3. Updating elements within a foreach loop.

Suppose the code fragment of Figure 3a was executed. Figure 3b shows the sequence of tuples that would be processed by the **foreach** loop during a "blind" retrieval. Blind or traditional database retrievals do not take into account changes (e.g., deletions) made to elements since the last composite cursor advancement. What is actually needed is a "validated" retrieval of n-tuples, where tests are performed prior to each composite cursor advancement to make sure that the next n-tuple is meaningful. Figure 3c shows the tuples produced during a validated retrieval.

P2 supports validation of n-tuples using the **valid** clause of a composite cursor declaration. The following declaration and code fragment eliminates the problems of a blind retrieval of (**department**, **employee**) tuples by returning tuples of undeleted elements:

```
compcurs < d department, e employee >
where "$d.deptno == $e.deptno"
valid "!deleted($d) && !deleted($e)" valid_composite_cursor;

foreach( valid_composite_cursor )
// Skips tuples with deleted elements.
{ delete( valid_composite_cursor.d ); }
```

Note that tuple validation is more general than merely testing for tuple deletion. P2 permits any predicate to be used for element validation. For example, the **deptno** field of a **department** element might be updated within a **foreach** loop. In this case, the **department** element has not been deleted, but its modification may affect the sequence of (valid) tuples that can be produced. Tuple validation is a general-purpose feature that is useful in graph traversal and garbage collection algorithms, where cursor validation is needed to ensure correct executions.

2.3 Type Expressions

P2 programs are written in terms of cursor, composite cursor, and container abstractions without regard to how these abstractions are implemented. The P2 compiler automatically translates P2 declarations and operations into C code. In order for P2 to accomplish this, P2 users must specify an implementation of these abstractions by composing building-blocks from the P2 library. Such a composition is declared in a **typex** (*type expression*) declaration:

```
typex { simple_typex = top2ds[qualify[dlist[malloc[transient]]]]; }
```

simple_typex is a composition of five P2 components. Each component encapsulates a consistent data and operation refinement of the cursor-container abstraction and is responsible for generating the code for this refinement [Sir93]. The **top2ds** layer, for example, translates **foreach** statements into primitive cursor operations (**reset**, **advance**, **end_of_container**); **qualify** translates qualified **advance** operations into **if** tests and unqualified **advance** operations; **dlist** connects all elements of a container onto a doubly-linked list; **malloc** allocates space for elements from a heap; and **transient** allocates heap space from transient memory. P2 code generation relies on sophisticated macro expansion and partial evaluation techniques [Bat93].

Altering a **typex** declaration yields a different implementation of cursors and containers. This powerful feature greatly assists tuning and maintaining P2 programs, as **typex** declarations generally account for a very small fraction of a P2 program.

3 The LEAPS Algorithms

As mentioned earlier, LEAPS produces the fastest executables of OPS5 rule sets, often outperforming OPS5 interpreters that use RETE-match or TREAT-match algorithms by several *orders* of magnitude [Bra91]. LEAPS translates OPS5 programs into C programs. Besides the expected performance gains made by compilation, LEAPS relies on special algorithms and sophisticated data structures to make rule processing efficient.

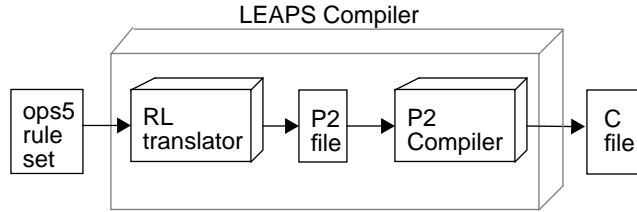


Figure 4. Relationship between LEAPS and P2

Figure 4 shows a relationship between the LEAPS compiler and P2. To reengineer LEAPS required us to translate OPS5 rule sets into a P2 program; this translator was called RL (*Reengineered Leaps*). The RL-generated P2 program would then be translated into a C program by the P2 compiler, thus effectively accomplishing in two translation steps what the LEAPS compiler does in one. All of the LEAPS algorithms are embedded in the generated P2 program. In this section, we show that the LEAPS algorithms have an elegant specification in P2. We assume that readers are familiar with the OPS5 language.

3.1 literalize Statements and OPS5 Terminology

OPS5 rule sets begin with “container” declarations called **literalize** statements:

```
(literalize guest name sex hobby)
```

The above statement declares a container **guest** whose elements have fields **name**, **sex**, and **hobby**. LEAPS infers the data types of element fields; we chose to augment **literalize** statements by supplying the data type for each field. Although this is a minor difference between LEAPS and RL, we note that the next generation of LEAPS (called VENUS [Bro94]), like RL, uses explicit typing of fields.

An OPS5 rule set is a sequence of rules/productions of the form:

```
(p make_path
  (context ^value make_path)
  (seating ^id <id> ^pid <pid> ^path_done no)
  (path ^id <pid> ^name <n1> ^seat <s>)
  -(path ^id <id> ^name <n1>)
  -->
  (make path ^id <id> ^name <n1> ^seat <s>))
```

The name of the above production is **make_path**. Each of the clauses prior to the arrow **-->** are called *condition elements* (CEs). The first three are *positive*; the last (with the minus sign) is *negative*. Positive condition elements serve two purposes: 1) to express qualifications on containers and 2) to declare variable bindings. For example, the first CE of the **make_path** rule qualifies elements from the **context** container to those whose **value** field is **'make_path'**. The second CE qualifies elements from the **seating** container to those whose **path_done** field is **'no'**; in addition, it sets variable **id** to the value of the **id** field of the qualified element and sets variable **pid** to the value of the **pid** field. The third CE qualifies elements from the **path** container whose **id** field equals the value of the variable **pid**; in addition, variable **n1** is assigned the value of the **name** field and variable **s** is assigned the value of the **seat** field. In all, the positive CEs of this rule identify 3-tuples (**context** element, **seating** element, **path** element) that satisfy a simple selection predicate.

Negated CEs are disqualification filters. The negated CE above disqualifies selected 3-tuples if there exists a **path** element whose **id** field matches the value of variable **id** and whose **name** field matches the value

of variable **n1** and whose **seat** field matches the value of **s**. In general, there can be any number of negated CEs in a rule; however, there must at least one positive CE.

Clauses that follow the arrow `-->` are the actions of the rule. Once an n-tuple has been qualified, it fires the actions of the rule. Actions of OPS5 rules include element creation, deletion, and modification; calls to routines external to OPS5 are possible. In the `make_path` rule, the sole action is to insert a path tuple whose `id` field equals variable `id`, whose `name` field equals variable `n1`, and whose `seat` field equals variable `s`.

3.2 LEAPS Overview

Forward-chaining inference engines, including LEAPS, use a match-select-action cycle. Rules that can be matched (i.e., tuples found to satisfy their predicates) are determined; one n-tuple is selected and its corresponding rule is fired. This cycle continues until a fix point has been reached (i.e., no more rules can be fired). RETE-match [For82] and TREAT-match [Mir91] algorithms are inherently slow, as they materialize all tuples that satisfy the predicate of a rule. Materialized tuples are stored in data structures and have a negative impact on performance as they must be updated as a result of executing rule actions. A fundamental contribution of LEAPS is the lazy evaluation of tuples; i.e., tuples are materialized only when needed. This approach drastically reduces both the space *and* time complexity of forward-chaining inference engines and provides LEAPS with its phenomenal increase in rule execution efficiency.

LEAPS assigns a timestamp to every element to indicate when the element was inserted or deleted. (For reasons that we will explain later, elements are not updated. Instead, the old version is deleted and a new version is inserted). Whenever an element is inserted or deleted, a handle to that element is placed on a stack. In general, the stack maintains a timestamp ordering of elements, where the most recently updated element is at the top of the stack and the least recently updated element is at the bottom.⁴

During a rule execution cycle, the top element of the stack is selected. This element is called the *dominant object* (DO). The DO is used to seed the selection predicates of all rules. Rules are considered for seeding in a particular order. Rules are sorted by their number of positive condition elements; the more positive CEs, the sooner the rule will be seeded. Many rules have the same number of positive CEs; these rules are seeded in order in which they were defined in the rule set. As soon as it is determined that the DO cannot seed a n-tuple for a given rule, the next rule is examined.⁵ When all rules have been considered, the DO is popped from the stack.

When a DO-seeded n-tuple is found, the corresponding rule is fired. The actions of the rule may invoke element insertions, deletions, and updates, which in turn will cause more elements to be pushed onto the stack. After a rule is fired, the selection of the next dominant object takes place. This execution cycle repeats; execution terminates when a fix-point is reached. This occurs when the stack is empty.

Note that an element may be pushed onto the stack twice: once when it is inserted and a second time when it is deleted. It is possible that a deleted element may be pushed onto the stack prior to the popping of its inserted element. That is, the stack may contain zero, one, or two references to any given element at any point in time.

4. There is an exception: an important LEAPS optimization violates the timestamp ordering. This optimization, called shadow optimization, is discussed in Section 3.5.

5. Actually, DOs cannot be used to seed all rules in general. If a DO is from container C and C is not referenced in the selection predicate of rule R, then the DO cannot seed R. Thus, the set of rules that a DO can seed can be pruned at compile time to only those that actually reference the DO's container.

The seeding of rule selection predicates by nondeleted elements has its obvious meaning. However, the seeding of rule predicates by deleted elements is not intuitively obvious, and its meaning is closely associated with the semantics of negation. Associated with every container C is a shadow container S. Every element that is deleted from C is inserted in S. The timestamp of an element e in C indicates when e was inserted; the timestamp of an element s in S indicates when s was deleted. Elements in S never undergo changes; they simply define the legacy of elements in C that previously existed. The purpose of shadow containers is to support time travel. The evaluation of negated CEs involves evaluating its predicate P on its container C over a period of time. That is, LEAPS asks questions like: is predicate P true from time t_0 to time t_1 ? The reason for this will become evident once the evaluation of negation is explained more fully.

In the following sections, we will give more technical precision to the above description.

3.3 Rule Translation

The difficult part of converting OPS5 rules into P2 code is the translation of rule predicates to P2 composite cursor declarations; translating the actions of rules is straightforward. There are six steps in rule predicate translation. The first is to convert qualifications of positive CEs to P2 predicates. Figure 5 shows the correspondence of a nonnegated rule predicate (Fig. 5a) with a composite cursor declaration (Fig. 5b). Note that each CE of the rule corresponds directly to a container that is to be joined. Also note that the use of `compcurs` aliases permit containers to be joined with themselves in an unambiguous way.

```
(p rule14
  (stage ^value labeling)
  (junction ^type tee ^base_point <bp>
    ^p2 <p1> ^p2 <p2> ^p3 <p3>)
  (edge ^p1 <bp> ^p2 <p1>)
  (edge ^p1 <bp> ^p2 <p3> ^label nil)
  -->

#define query14 "$a.value == 'labeling' &&
  $b.type == 'tee' &&
  $c.p1 == $b.base_point &&
  $c.p2 == $b.p1 &&
  $d.p1 == $b.base_point &&
  $d.p2 == $b.p3 &&
  $d.label == 'nil'"

typedef compcurs < a stage, b cont_junction,
  c cont_edge, d cont_edge >
  where query14 curs14;
```

Figure 5a-b. Rule Translation Step 1: Conversion of Selection Predicates

Recall that a central concept of rule processing in LEAPS is the seeding of rules by dominant objects. In order to support seeding, multiple copies of an OPS5 rule are spawned, one copy of each different condition element that is being seeded. The second step in the rule translation process is to replicate a composite cursor definition, one copy for each possible seed position. Figure 6a shows the format of a cursor declaration produced in Step 1; Figure 6b shows the replication of this rule with different seeds. Note that the effect of this rewrite is to translate an n-way join to a more efficient (n-1)-way join.

OPS5 semantics imposes a fairness criterion that no n-tuple can fire a rule more than once. Fairness is achieved in LEAPS through the use of timestamps and temporal qualifications. Every element has a timestamp that indicates when it was last updated (i.e., inserted or deleted). OPS5 semantics are realized by requiring all elements of an n-tuple to have their timestamps less than or equal to the timestamp of the dominant object that seeded the n-tuple.⁶ Figure 7a shows the format of a cursor declaration produced in Step 2; Figure 7b shows the addition of temporal predicates to the `where` clause of the cursor. `_ts` is the name of the timestamp field for every element.

Once a rule is fired, the composite cursor is placed on a stack, thereby suspending its execution. At some later time, when the element that seeded the composite cursor again becomes dominant, the composite cursor is popped and advanced to the next n-tuple. During the time the cursor is on the stack, any or all of the

```

typedef compcurs < a .., b .., c .., d .. >
  where query14 curs14;

typedef compcurs < a .., b .., c .., d .. >
  given < a >
  where query14 curs14_a;

typedef compcurs < a .., b .., c .., d .. >
  given < b >
  where query14 curs14_b;

typedef compcurs < a .., b .., c .., d .. >
  given < c >
  where query14 curs14_c;

typedef compcurs < a .., b .., c .., d .. >
  given < d >
  where query14 curs14_d;

```

Figure 6a-b. Rule Translation Step 2: Replication of Composite Cursors by Seeding

```

typedef compcurs < a .., b .., c .., d .. >
  given < a >
  where query14 curs14_a;

#define temporal_query14
  "$b._ts <= dominant_timestamp &&
  $c._ts <= dominant_timestamp &&
  $d._ts <= dominant_timestamp"

typedef compcurs < a .., b .., c .., d .. >
  given < a >
  where query14 "&&" temporal_query14
  curs14_a;

```

Figure 7a-b. Rule Translation Step 3: Addition of Temporal Predicates

elements of the last n-tuple it produced could have been modified or deleted. Consequently, advancements of composite cursors must be validated. This is accomplished by adding a valid predicate to each cursor declaration. Figure 8a shows a cursor definition produced in Step 3; Figure 8b shows the addition of the valid predicates.⁷

```

typedef compcurs < a .., b .., c .., d .. >
  given < a >
  where query1 "&&" temporal_query14
  curs14_a;

#define valid_query "!is_deleted($a) &&
  !is_deleted($b) &&
  !is_deleted($c) &&
  !is_deleted($d)"

typedef compcurs < a .., b .., c .., d .. >
  given < a >
  where query14 "&&" temporal_query14
  valid valid_query14
  curs14_a;

```

Figure 8a-b. Rule Translation Step 4: Addition of Validation Predicates

6. Things are actually a bit more complicated. In the case where a container C is being joined with itself, we want to eliminate pairs of the same object (c,c) which could be generated more than once. To avoid such duplication, timestamp qualifications on containers “to the left” of the container of the seeding dominant object to have timestamps \leq the timestamp of the DO and qualifications on containers “to the right” of the seeding container to be $<$ the timestamp of the DO [Bra93b]. The notion of “left” and “right” is determined by the order in which containers are listed to be joined. Note that LEAPS *did* generate multiple tuples as it did not enforce the ideas outlined in this footnote.

7. Technically, cursors are not popped off the stack; pointers to cursors are overwritten. A stack item contains a pointer to an element, the identifier of the container to which the element belongs, a pointer to a composite cursor whose execution has been suspended, and an identifier of the rule to which the composite cursor belongs. When a cursor is popped, the cursor pointer is set to null. A stack item is popped only when all rules have been seeded.

Negated CEs are disqualification filters. The LEAPS interpretation of negation is depicted in Figure 9. An element e is created at time t_0 and seeds an n-tuple by advancing a composite cursor at times $t_1 \dots t_4$. Let P be the predicate of a negated CE and t be the time of a composite cursor advancement. LEAPS determines if P is true at time t or at any time since e has been created.

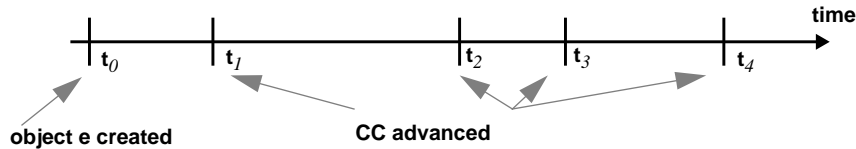


Figure 9. Interpretation of Negation

This interpretation has two significant consequences. First, LEAPS must maintain a history of all container elements so that time can be “rolled back” to evaluate P . This is realized by creating a *shadow container* for each container to be a repository of the versions of elements that have since been modified or deleted. Because shadow elements are tagged with the timestamp of their removal from the primary (nonshadow) container, time travel is possible. Shadow containers are a major source of complexity in LEAPS. Second, because predicate P may be valid at some time t does not mean that P is valid at later times. Consequently, predicate P must be used to filter elements both in the **where** clause of a composite cursor and in the **valid** clause as well. Figure 10a shows a rule with negation and Figure 10b shows one of its P2 composite cursor counterparts (i.e., the one seeding in position **a**). Note that $N5_4(\dots)$ is a boolean function (generated by RL) that expresses the filter of the negated CE.⁸

```
(p rule5
  (stage ^value detect_junctions )
  (edge ^p1 <bp> ^p2 <p2> ^joined false )
  (edge ^p1 <bp> ^p2 <p3> ^p2 <> <p2>
    ^joined false )
  -(edge ^p1 <bp> ^p2 <> <p2> ^p2 <> <p3> )
-->

#define query5
  "$a.value == 'detect_junctions' &&
  $b.joined == 'false' &&
  $c.p1 == $b.p1 &&
  $c.p2 != $b.p2 &&
  $c.joined == 'false' &&
  N5_4(&$b,&$c)"

#define temporal_query5
  "$a._ts <= dominant_timestamp &&
  $b._ts <= dominant_timestamp &&
  $c._ts <= dominant_timestamp"

#define valid_query5
  "!is_deleted($a) &&
  !is_deleted($b) &&
  !is_deleted($c) &&
  N5_4(&$b,&$c)"

typedef compcurs < a cont_stage, b cont_edge,
                  c cont_edge >

given < a >
where query5 && temporal_query5
valid valid_query5
curs5_a;
```

Figure 10a-b. Rule Translation Step 5: Placement of Negated Predicate Filters

8. Negated CE filters, like $N5_4(\dots)$ have a simple realization in P2. The filter is (1) to test the container of the negated CE for any element that satisfies predicate P of the negated CE, and (2) to examine the corresponding shadow container if any element satisfies P and whose timestamp is greater than the dominant timestamp. If qualified elements are found in either container, $N5_4(\dots)$ returns false. Both qualifications can be easily expressed using cursors with the obvious selection predicates over the container and shadow container.

Finally, it is possible for shadow container elements to become dominant. The idea here is that a container element may block the qualification of n-tuples because it satisfied a negated CE filter. With the deletion of this element, previously disqualified (or *blocked*) n-tuples may now be qualified (*unblocked*). Tests for unblocked tuples are created by (a) modifying the original OPS5 rule by replicating the negated CE as a positive CE, (b) converting the resulting rule via the translation steps we have just outlined, and (c) seeding the resultant composite cursor with the shadow object. Figure 11a shows the result of step (a) to the rule of Figure 10a; Figure 11b shows the translation resulting from (b) and (c).

```

(p rule5
  (stage ^value detect_junctions )
  (edge ^p1 <bp> ^p2 <p2> ^joined false )
  (edge ^p1 <bp> ^p2 <p3> ^p2 <> <p2>
    ^joined false )
  (edge ^p1 <bp> ^p2 <> <p2> ^p2 <> <p3> )
  -(edge ^p1 <bp> ^p2 <> <p2> ^p2 <> <p3> )
  -->

# define query5d
  "$a.value == 'detect_junctions' &&
  $b.joined == 'false' &&
  $c.p1 == $b.p1 &&
  $c.p2 != $b.p2 &&
  $c.joined == 'false' &&
  $d.p1 == $b.p1 &&
  $d.p2 != $b.p2 &&
  $d.p2 != $c.p2 &&
  N5_4(&$b,&$c)"

# define temporal_query5d
  "$a._ts <= dominant_timestamp &&
  $b._ts <= dominant_timestamp &&
  $c._ts <= dominant_timestamp &&
  $d._ts <= dominant_timestamp"

# define valid_query5d
  "!is_deleted($a) &&
  !is_deleted($b) &&
  !is_deleted($c) &&
  !is_deleted($d) &&
  N5_4(&$b,&$c)"

typedef compcurs < a cont_stage, b cont_edge,
  c cont_edge, d shadow_edge >
  given < d >
  where query5d && temporal_query5d
  valid valid_query5d
  curs5_d;

```

Figure 11a-b. Rule Translation Step 6: Seeding of Shadow Elements

3.4 Other Issues

There are additional issues regarding the translation of OPS5 rule sets into P2 programs that are worth mentioning. First, when an element is inserted in LEAPS, it is pushed onto a wait-list stack for subsequent seeding. Composite cursors, whose execution was suspended, are placed on a join-stack. The stack whose top element has the most recent timestamp is chosen to be the dominant object on the next execution cycle. In RL (and in other versions of LEAPS), the wait-list stack and join stack are unified. This gives a very compact and elegant representation of the primary cycle loop (see Figure 12a). Note that the “unified” stack is represented as a container, and **top** is a cursor that references the top element of the stack.

The procedures for rule firings are also compact (see Figure 12b). If a cursor has not yet been created (i.e., \neg **fresh**), one is malloced from the heap, initialized, and positioned on the seeding element. Control then falls to the **foreach** statement. If a cursor has been created (and whose execution has been suspended), control continues at the end of the **foreach** statement (where validation tests are performed by P2). Once an n-tuple is generated, the rule is fired and the procedure is exited. After all n-tuples have been generated, control passes to the next rule for possible firing.

```

execute_production_system()
{
    while(1) {
        // Get the top of the stack.
        reset_start(top);
        if (end_of_container(top)) {
            // The stack is empty.
            // We're at a fix-point.
            break;
        }
        else {
            // The stack is not empty.
            fresh = !top.curs;
            dom_timestamp = top.time_stamp;
            (*top.current_rule());
        }
    }
}

void seed_rule14_a ( void )
{ curs14_a *c;

    if (fresh) {
        c = (curs14_a*)malloc(sizeof(curs14_a));
        top.curs = (void*) c;
        initk(*c);
        position(c->a,top.cursor_position);
    } else {
        c = (curs14_a *) top.curs;
        goto cnt;
    }

    foreachk(*c) {
        fire_rule14_a( c );
        return;
    }

cnt: ; // perform valid tests here
}

free(c);
fresh = TRUE;
top.current_rule = nextrule;
nextrule(); // call seed_rule proc for
// next rule firing
}

```

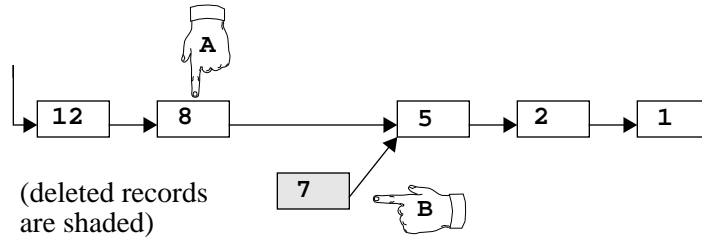
Figure 12a-b. Execution Cycle and Rule Seeding Procedures

3.5 Notes on Data Structures

We stated earlier that elements are not updated, but rather deleted and then reinserted. While this seems odd, it actually plays an integral role in the design of the LEAPS data structures for containers. The basic idea is that composite cursors on the unified stack may point to elements that have been deleted. To advance a composite cursor in such situations, elements can only be logically deleted (i.e., flagged deleted); their storage space cannot be physically reclaimed. (Or more accurately, their storage space cannot be reclaimed until no cursor is referencing it). Hence the need for modeling updates as deletions followed by insertions.

LEAPS performed rudimentary garbage collection, where the physical space of elements is reclaimed. We noted that maintaining reference counts (or whatever LEAPS actually does) adds considerable run-time overhead. For the applications of LEAPS that we have seen, garbage collection at fix-point time offers a much faster and simpler way to accomplish garbage collection.

Another unusual requirement for a LEAPS container data structure is that elements must be stored in descending timestamp order. One reason is to maintain OPS5 semantics. Another is to be consistent with the general expert-system philosophy that the n-tuple that is selected for rule firing should have the most recent timestamps. The simplest data structure that LEAPS could use as a container implementation is a doubly-linked list, where deleted elements are still “connected” in that cursors on deleted elements can be advanced to nondeleted elements. The figure below shows two cursors on a container (implemented by a list). Cursor **A** points to an element with timestamp 8; cursor **B** points to a deleted element with timestamp 7). When cursor **B** is advanced, it will be positioned on the next undeleted element of the container whose timestamp is less than 7. In general, it is possible that **B** may need to traverse a chain of deleted elements before the first undeleted element is reached.



4 Optimizations

LEAPS (and RL) include a variety of optimizations than enhance the basic algorithms outlined in Section 3. We explain the major optimizations in this section.

Timestamp Ordered Lists. A timestamp ordered list is a doubly-linked list where (undeleted) elements are maintained in descending timestamp order. Unlike “standard” doubly-linked lists, timestamp ordered lists perform query modifications for optimizations. For example, a typical rule selection predicate requires element timestamps to be less than or equal to the dominant timestamp. A timestamp ordered list would use this requirement to optimize the `reset_start` operation, which positions a cursor on the first record that satisfies the selection predicate. What happens is that the timestamp predicate is applied to the first elements of the list until an element qualifies. From that point on, there is no need for qualifying subsequent elements due to timestamp ordering. Thus, predicates applied to subsequent elements do not involve temporal qualification. Other types of query optimizations with timestamp ordered lists are possible; readers are encouraged to see the `tlist[]` component in the P2 library.

Predicate Indices. A *predicate index* is a list of elements of a container that satisfy a given predicate. (In the AI literature, predicate indices are called *alpha memories*). Predicate indices are quite useful in LEAPS/RL, as the selection predicates of rules are static. For example, to minimize the search time for finding `stage` elements whose `value` field has “labeling” (in `rule14` of Figures 5-8), a predicate index for `stage` using predicate “`$.value == 'labeling'`” is used. In general, a predicate index is created for each positive (and negative) condition element of a rule that references constants. Again looking at `rule14` as an example, the following predicate indices would be created:

Condition Element #	Container	Predicate to index (empty if no index created)
#1	<code>stage</code>	<code>\$.value == 'labeling'</code>
#2	<code>junction</code>	<code>\$.type == 'tee'</code>
#3	<code>edge</code>	
#4	<code>edge</code>	<code>\$.label == 'nil'</code>

A predicate index component in P2, `predindx[]`, is a minor modification of `tlist[]`.

Active Rule Optimization. k -way joins can lead to $O(n^k)$ execution times, where n is the number of elements in a container. Eliminating costly searches that are known, a priori, not to yield n -tuples, often provides great performance advantages. The *active rule optimization* is the skipping of rules to be seeded because it is known that the rule cannot generate n -tuples. This optimization requires the presence of predicate indices. When a predicate index is an empty list (i.e., there are no elements in the container that satisfy the given selection predicate), we know that a seeded rule cannot produce n -tuples. It is a simple matter to augment the definition of the predicate index layer to accept as a further annotation two procedures. One procedure is called when the predicate index becomes empty; another procedure is called when

the predicate index becomes nonempty. The procedures themselves merely increment a counter for each rule that uses the predicate index. If the counter for a rule is nonzero (meaning that there are one or more predicate indices that are null), we know that the rule can be skipped for seeding. If the count is zero, seeding the rule may produce n-tuples.

In RL, we examine the counter for every rule that could be seeded by a dominant object. Thus, if there are n rules, there are n tests. In general, the number of rules that are active at any one time is rather small. Thus, if the list (container?) of active rules is maintained dynamically, performance of LEAPS should be enhanced. In particular, we conjecture that as the number of rules per rule set increases, a scheme to maintain dynamically the list of rules may offer significant performance advantages.

Symbol Tables. String comparisons are always costly. A more efficient way to perform string comparisons is to enter strings into a symbol table and to compare handles to strings. Since OPS5 allows only == and != operations on strings, handle comparisons work well. This optimization is also called *string constant enumeration*.

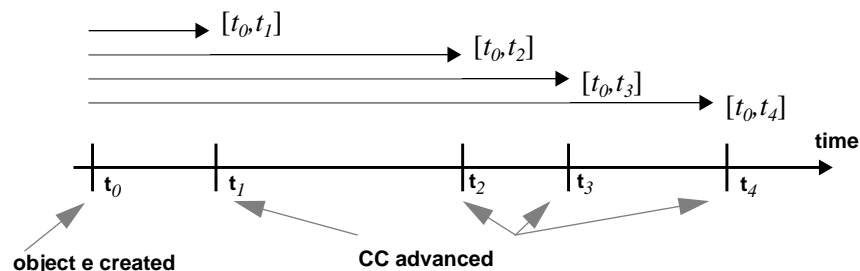
Shadow Stacking. We explained earlier that the unified stack maintains a timestamp ordering of its elements; the top element has the most recent timestamp and the bottom element has the oldest. Deleted objects are called *shadows*. Experience has shown that shadows rarely succeed in seeding rules (i.e., producing n-tuples to fire). As there can be many shadows on the stack at any given moment, a large fraction of LEAPS run time is consumed processing shadows.

A way to minimize the processing time for shadows is to place them at *bottom* of the stack, rather than at the top. This invalidates the property that the stack maintains elements in descending timestamp order, but has the advantage that shadow processing becomes more efficient (i.e., particularly in the presence of active rule optimizations). The increase in LEAPS performance can be dramatic with shadow stacking.

Hashed Timestamp Ordered Lists. The standard LEAPS data structure is a timestamp ordered list, described above. The standard LEAPS join algorithm is nested loops. A way to improve the performance of LEAPS dramatically would be to use hashed timestamp ordered lists. The idea is simple: instead of maintaining a single list of timestamp ordered elements, b lists are maintained, one list per bucket. Bucket assignments of elements are based on a hash key, which should also be a join key. As a result, search times for elements on inner loops of joins are reduced by a factor of b (i.e., a fraction of (b-1)/b of the elements have been eliminated as they don't hash to the right join key). Hashed timestamp ordered lists (`hlist[]`) is a simple variation on timestamp ordered lists (`tlist[]`); hashed timestamp ordered predicate indices (`hpredindx[]`) is a simple variation on predicate indices (`predindx[]`).

In general, the idea of using “hash” joins to obtain improved performance is an obvious consequence of the work of Brant and Miranker [Bra93a].

Negation Optimization. Experience has shown that the following is not an effective optimization, but it is an interesting idea never-the-less. Recall Figure 9 that helps illustrate the meaning of negation:



A great deal of time is spent evaluating predicates of negated condition elements. In the case that a dominant object can seed multiple n-tuples (as in the above figure where object e seeds 4 n-tuples), it is possible to optimize the processing of predicates of negated CEs. The idea is simple: when the negated CE is applied to tuple at time t_2 , the truth value of its predicate must be determined for the interval $[t_0, t_2]$. Note that the predicate must have been true for all previously tested intervals, e.g., $[t_0, t_1]$, since had the predicate failed, it would not be possible to seed further tuples. The optimization is to avoid replicate evaluation of a negated predicate over the same interval. To test the validity of a predicate in interval $[t_0, t_2]$, it is sufficient to test the validity only over the interval $[t_1, t_2]$, as the truth of the predicate in $[t_0, t_1]$ has already been established.

As mentioned above, experience has shown that a dominant object typically seeds at most one n-tuple per rule. Consequently, the conditions for the above optimization don't seem to arise.

Malloc optimization. The Unix `malloc` optimization is very slow. LEAPS relied on its own memory allocation scheme. We tried to do something similar with a layer in P2 which performs the duties of `malloc` on our own, home-grown memory allocation scheme. As it turns out, `gnu malloc` is more efficient, so we did not pursue `malloc` optimization further.

5 RL Implementation

Of course, there are lots of details of LEAPS that are not explained in this paper. We recommend that the interested readers examine the P2 files that are generated by RL. These files have embedded comments and are fairly easy to understand with this paper.

When RL is run without command line arguments, the following options are shown:

```
Usage: rl [options] file
      file.ops read; file.p2 is generated (see -s option)
Options:
  -a active rule optimization
  -c string constant enumeration optimization
  -d debugging mode for op code generation
  -e leaps debugging mode
  -h shadow stacking optimization
  -i inline insert and delete operations
  -l standard leaps options (-achmp)
  -m malloc optimization
  -n negation optimization
  -p predicate indexing included
  -s print to standard output, not file.p2
  -t include timestamp layer
  -x add attribute indices
  -1 no explicit shadow container
```

The `-achlmp` options were discussed as optimizations in Section 4. The `-de` options are purely for debugging RL. Options `-x1` are not fully implemented. The `-t` option has not been fully tested, but whether or not it is selected should make little or no difference in performance. (RL generates timestamps to match those of LEAPS when `-t` is not selected; if `-t` is selected, a timestamp layer assigns timestamps).

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