Software Design Alternatives and Examples

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Deep Thought

- According to C.A.R. Hoare, there are two methods of constructing a software system:
  1. One way is to make it so simple that there are obviously no deficiencies
  2. The other way is to make it so complicated that there are no obvious deficiencies

Introduction

- A key question facing software architects and designers is:
  - Should software systems be structured by *actions* or by *data*?
  - This decision cannot be postponed indefinitely
    - ∗ Eventually, a designer must settle on one or the other
    - ∗ Note, the source code reveals the final decision...
- *Observation*:
  - The tasks and functions performed by a software system are often highly volatile and subject to change
- *Conclusion*:
  - Structuring systems around classes and objects increases continuity and improves maintainability over time for large-scale systems
  - Therefore, "ask not what the system does: ask what it does it to!"

Outline

- This set of slides examines several alternative design methodologies
  - Primarily algorithmic/functional design vs. object/component-oriented design
- These alternatives differ in terms of aspects such as
  1. Decomposition and composition criteria
     - *e.g.*, algorithms/functions vs. objects/components
  2. Support for reuse and extensibility, *e.g.*,
     - Special-purpose vs. general-purpose solutions
     - Tightly-coupled vs. loosely-coupled architectures
  3. Scalability
     - *e.g.*, programming-in-the-small vs. programming-in-the-large

Overview of Algorithmic Design

- Top-down design based on the *functions* performed by the system
- Generally follows a "divide and conquer" strategy based on functions
  - *i.e.*, more general functions are iteratively/recursively decomposed into more specific ones
- The primary design components correspond to processing steps in the execution sequence
  - Similar to a recipe for cooking a meal
    - Consider the objects and recipes used in cooking...

Overview of Object-oriented Design

- Design based on modeling classes and objects in the application domain
  - Which may or may not reflect the "real world"
- Generally follows a "hierarchical data abstraction" strategy where the design components are based on classes, objects, modules, and processes
- Operations are related to specific objects and/or classes of objects
- Groups of classes and objects are often combined into frameworks

Structured Design

- Design is based on data structures input and output during system operation
- Generally follows a decomposition strategy based on data flow between processing components
- Primary design components correspond to flow of data
  - Program structure is derived from data structure
  - Data structure charts show decomposition of input/output streams
- Often used as the basis for designing data processing systems
- Design tends to be overly dependent upon temporal ordering of processing phases, *e.g.*, initialize, process, cleanup
- Changes in data representations ripple through entire structure due to lack of information hiding

Transformational Systems

- Design is based on specifying the problem, rather than specifying the solution
  - The solution is automatically derived from the high-level specification
  - Note, each transformation component may be implemented via other design alternatives
- Limited today to well-understood domains
  - *e.g.*, parser-generators, GUI builders, signal processing

Criteria for Evaluating Design Methods

- *Component Decomposability*
  - Does the method aid decomposing a new problem into several separate subproblems?
    - *e.g.*, top-down algorithmic design
- *Component Composability*
  - Does the method aid constructing new systems from existing software components?
    - *e.g.*, bottom-up design
- *Component Understandability*
  - Are components separately understandable by a human reader
    - *e.g.*, how *tightly coupled* are they?

Criteria for Evaluating Design Methods (cont'd)

- *Component Continuity*
  - Do small changes to the specification affect a localized and limited number of components?
- *Component Protection*
  - Are the effects of run-time abnormalities confined to a small number of related components?
- *Component Compatibility*
  - Do the components have well-defined, standard and/or uniform interfaces?
    - *e.g.*, "principle of least surprise"

Case Study: Spell Checker Example

- System Description
  - 'Collect words from the named document, and look them up in a main dictionary or a private, user-defined dictionary composed of words. Display words on the standard output if they do not appear in either dictionary, or cannot be derived from those that do appear by applying certain inflections, prefixes, or suffixes'
- We first examine the *algorithmic* approach, then the *object-oriented* approach
  - Note carefully how changes to the specification affect the design alternatives in different ways...

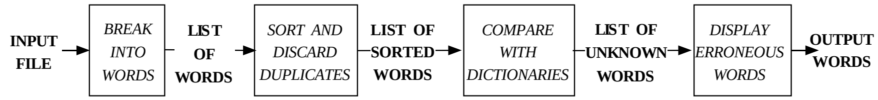
High-level Application Description

- Pseudo-code algorithmic description
  1. Get document file name
  2. Splits document into words
  3. Look up each word in the main dictionary and a private dictionary
     (a) If the word appears in either dictionary, or is derivable via various rules, it is deemed to be spelled correctly and ignored
     (b) Otherwise, the "misspelled" word is output
- Note, avoid the temptation to directly refine the algorithmic description into the software architecture...

Program Requirements

- Initial program requirements and goals:
  1. Must handle ASCII text files
  2. Document must fit completely into main memory
  3. Must run “quickly”
     – Note, document is processed in batch” mode
  4. Must be smart about what constitutes misspelled words (that’s why we need prefix/suffix rules and a private dictionary)
- Two common mistakes:
  1. Failure to flag misspelled words
  2. Incorrectly flag correctly spelled words

Data Flow Diagram



- While this diagram is useful for “describing” high-level flow of data and control, avoid the temptation to refine it into system design and implementation...

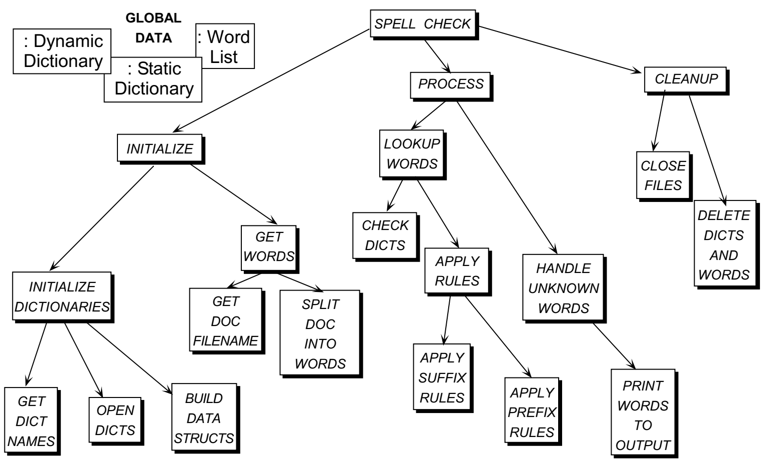
Algorithmic Design (1/2)

- Spell checker program is organized according to activities carried out during program execution
  – *i.e.*, system is completely specified by the functions that it performs
- Function refinement precedes and guides data refinement
- *Important questions*:
  1. How is design affected by subsequent changes to the specification and/or implementation?
  2. How reusable are the algorithmic components developed via the approach?

Algorithmic Design (2/2)

- Top-down, iterative “step-wise” refinement of functionality:
  1. Break the overall “top” system function into subfunctions
  2. Determine data flow between these functions, *then* determine data structures
  3. Iterate recursively over subfunctions until implementation is immediate and “obvious”
- Structure chart shows function hierarchy and data flow
  – Hierarchical organization is a tree with one functional activity per node

Algorithm Design Structure



Algorithm Design Program

```
struct List {
  char *word;
  struct List *next, *prev;
} *list = 0;
extern struct Static_Dictionary main_dict;
extern struct Dynamic_Dictionary private_dict;

int main (int argc, char *argv[]) {
  initialize (); /* Perform initializations */
  process (); /* Perform lookups */
  cleanup (); /* Deallocate resources */
}

int process (void) {
  for (struct List *ptr = list;
       ptr != 0;
       ptr = ptr->next)
    if (static_lookup (&main_dict, ptr->word) ||
        dynamic_lookup (&private_dict, ptr->word))
    {
      struct List *tmp = ptr;
      ptr->prev->next = ptr->next;
      free (tmp);
    }
  handle_unknown_words ();
}
```


Advantages of Algorithmic Design

- Reasonably well-suited for small-scale, algorithmic-intensive programs
  - *e.g.*, Eight-Queens problem, Towers of Hanoi, 8-tiles problem, sort, and searching, *etc.*
- Easy to understand for small problems
  - Since system structure matches verbal, algorithmic description
- "Intuitive" to many designers and programmers
  - Due to emphasis in early training...

Disadvantages of Algorithmic Design

- Fails to account for long-term system evolution
  - *i.e.*, changes in algorithms and data structures ripple through entire program structure (and the documentation...)
  - Implementation often typified by lack of information hiding, combined with an over-abundance of global variables
    - ∗ These characteristics are not inherent, but are often related...
- Does not promote reusability
  - The design is specifically tailored for the requirements and specifications of a particular application
- Data structure aspects are often underemphasized
  - They are postponed until activities have been defined and ordered

Object-Oriented Design (1/2)

- Development begins with extensive domain analysis on the problem space
  - *i.e.*, OOD is not a "cookbook" solution
- Decompose the spell checker by *classes* and *objects*, not by overall processing *activities*
- Organize the program to hide implementation details of information that is likely to change
  - *i.e.*, use abstract data types and information hiding
- The order of overall system *activities* are not considered until later in the design phase
  - However, activities are *not* ignored!

Object-Oriented Design (2/2)

- At first glance, our object-oriented design appears to be incomplete since it does not seem to address the overall system *actions*...
- This is intentional, however, and supports the software design principle of "underspecification"
  - The goal is to develop reusable components that support a "program family" of potential solutions to this and other related problems
- In fact, the main processing algorithm may be quite similar in both algorithmic and object-oriented solutions...

Key Challenges of Object-Oriented Design

- A common challenge facing developers is finding the objects and classes
  - One approach: 'Use parts of speech in requirements specification statements to':
    1. Identify the objects
    2. Identify the operations and attributes
    3. Establish the interactions and visibility
  - This methodology is not perfect, but it is a good place to start...
    - *i.e.*, apply it at various levels of abstraction during development
- Another challenge is to ensure that the design can be mapped to an implementation that meets end-to-end QoS requirements

Classifying Parts of Speech

- Example: *Spell Checker*
  - *Collect* **words** from the `named` **document**, and *look them up* in a `main` **dictionary** or a `private user-defined dictionary` composed of **words**. *Display* **words** on the `standard` **output** if they do not appear in either **dictionary**, or cannot be *derived* from those that do appear by *applying* certain **inflections**, **prefixes**, or **suffixes**
- Relevant parts of speech:
  - **Common nouns** → classes
  - `Proper` **nouns** → objects
  - *Verbs* → actions on objects

Identifying Classes and Objects for the Spell Checker

- Common noun → class
  - *e.g.*, **spell checker**, **dictionary**, **document**, **words**, **output**
- Proper noun or direct reference → object
  - `named` **document**, `main` **dictionary**, `private` **dictionary**, `standard` **output**
- Describe using UML notation, CRC cards ("class, responsibility, collaborators"), C++ classes, *etc.*

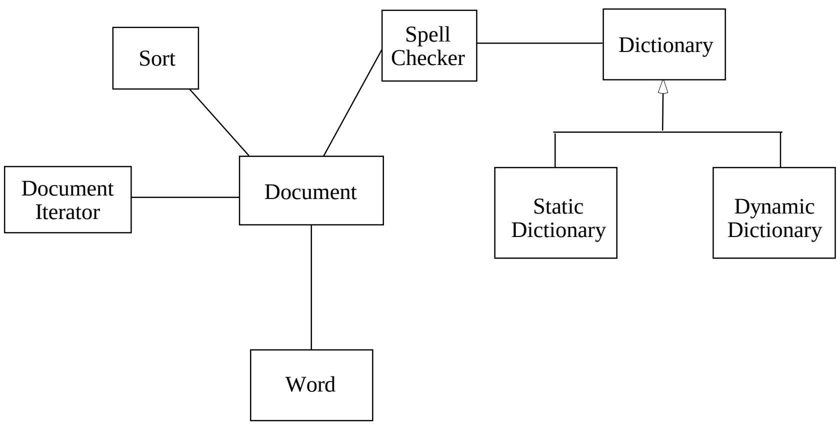
Identifying Operations and Attributes for the Spell Checker

- Verb → operations performed on a class or by an object of a class
  - *e.g.*, `collect` (document), `look up` (dictionary), `display` (word)
- Adverb → constraint on an operation
  - *e.g.*, `insert_quickly` (*i.e.*, no range checking)
- Adjective → attribute of an object
  - *e.g.*, "large" dictionary → size field
- Object of verb → object dependencies
  - *e.g.*, "A dictionary composed of words"

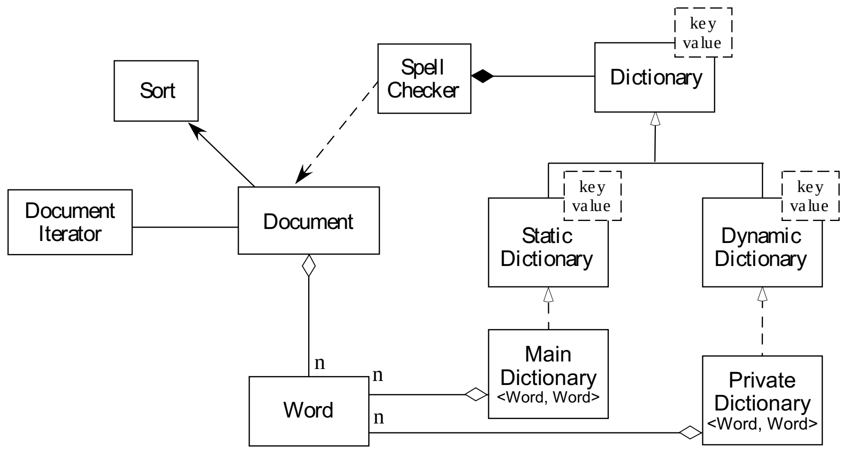
Applying the Object-Oriented Method

- Visibility should satisfy dependencies and no more
  - In general, reduce global visibility, de-emphasize coupling, emphasize cohesion
  - In particular, `Document` and `Dictionary` shouldn't be visible outside context of `Spell_Checker`...
- Develop a set of diagrams that graphically illustrate class, object, module, and process relationships from various perspectives

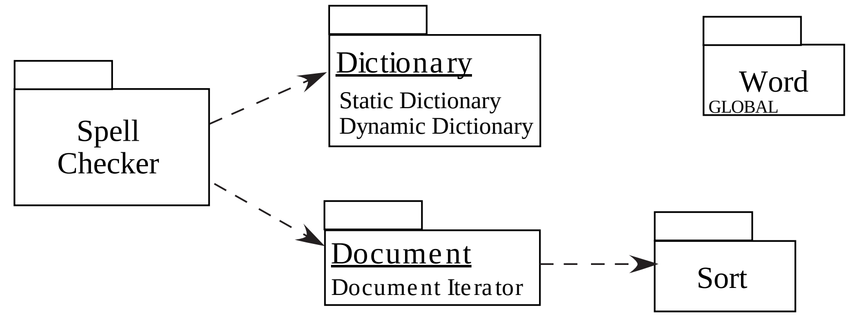
High-level Class Diagram



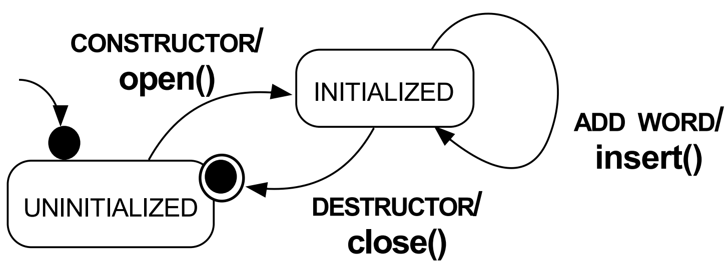
Detailed Class Diagram



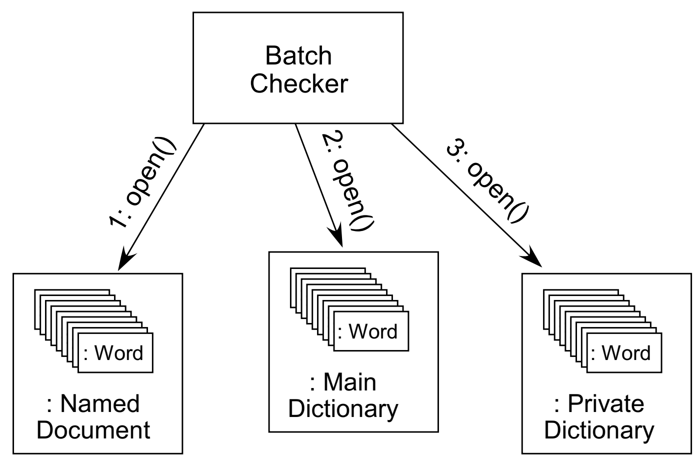
Package Diagram



State Machine Diagram for Dictionary class



Object Diagram



General Class Descriptions (cont'd)

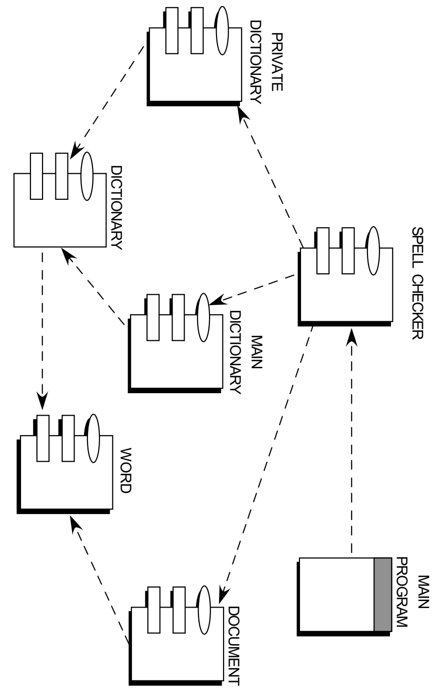
- Building block classes (cont'd)

```
NAME            Dictionary
QUALIFICATIONS  Abstract class
ACCESS          Exported
CARDINALITY     Unlimited
MEMBERS         construct/destruct
    open/close
                insert word
                find word
                remove word
                next word iterator
                ...

NAME            Dynamic Dictionary
ACCESS          Exported
CARDINALITY     Unlimited
SUPERCLASS      Dictionary
MEMBERS         construct/destruct
                ...

NAME            Static Dictionary
ACCESS          Exported
CARDINALITY     Unlimited
SUPERCLASS      Dictionary
MEMBERS         construct/destruct
                ...
```


Module Diagram



Concrete Class Descriptions

- Building block classes (C++ notation for class interface description)

```
class Word {
public:
  Word (void);
  Word (const string &);
  int insert (int index, char c);
  int clone (Word &);
  int concat (const Word &);
  int compare (const Word &);
  // ...
};

class Document {
public:
  Document (void);
  ~Document (void);
  virtual int open (const string &filename);
  int sort (int options);
  // ...
};

class Document_Iterator {
public:
  Document_Iterator (const Document &);
  int next_item (Word &);
  // ...
};
```


General Class Descriptions

- Building block classes (abstract notation for class interface description)

```
NAME            Word
ACCESS          Exported
CARDINALITY     Unlimited
MEMBERS         construct/destruct
                insert/remove characters
                clone
                concatenate
                compare
                ...

NAME            Document
ACCESS          Exported
CARDINALITY     Unlimited
MEMBERS         construct/destruct
                next word iterator
                sort
                ...

NAME            Spell_Checker
ACCESS          Exported
CARDINALITY     Unlimited
MEMBERS         construct/destruct
                spell_check
                ...
```

Concrete Class Descriptions (cont'd)

- Building block classes (C++ notation for class interface description)

```
namespace Dictionary {
template <class KEY, class VALUE>
class Dictionary {
public:
  virtual int open (const string &filename) = 0;
  virtual find (KEY, VALUE &) = 0;
  virtual insert (KEY, VALUE &) = 0;
  virtual remove (KEY) = 0;
  // ...
};

template <class KEY, class VALUE>
class Dynamic_Dictionary : public Dictionary {
public:
  virtual int open (const string &filename);
  virtual find (KEY, VALUE &);
  // ...
};

template <class KEY, class VALUE>
class Static_Dictionary : public Dictionary {
public:
  virtual int open (const string &filename);
  virtual find (KEY, VALUE &);
  // ...
};
}
```


Concrete Class Descriptions (cont'd)

- Building block classes (C++ notation for class interface description)

```
#include "Document.h"
#include "Static_Dictionary.h"
#include "Dynamic_Dictionary.h"

using namespace Dictionary;
typedef Static_Dictionary<Word, Word> Main_Dictionary;
typedef Dynamic_Dictionary<Word, Word> Private_Dictionary;

class Spell_Checker {
public:
  ~Spell_Checker (void);
  int open (const string &doc_name,
            const string &main_dict_name,
            const string &private_dict_name);
  int spell_check (ostream &standard_output);
private:
  Document named_document;
  Main_Dictionary main_dictionary;
  Private_Dictionary private_dictionary;
};
```


Spell checker Implementation

- Main class

```
Spell_Checker::Spell_Checker (const string &doc_name,
                              const string &main_dict_name,
                              const string &private_dict_name)
{
  if (named_document.open (doc_name) == -1
      || main_dictionary.open (main_dict_name) == -1
      || private_dictionary.open (private_dict_name) == -1) {
        cerr << "intialization problem";
        throw Invalid_Name ();
  }
}
```


Spell checker Implementation

- Main class (cont'd)

```
int Spell_Checker::spell_check (ostream &standard_output)
{
  int result = 0;
  Word word;
  named_document.sort (REMOVE_DUPS);
  for (Document_Iterator doc_iter (named_document);
       doc_iter.next_item (word) != -1; )
    if (main_dictionary.find (word) != -1
        || private_dictionary.find (word) != -1)
      continue; // found word
    else {
      standard_output.write (word);
      // erroneous word
      result = -1;
    }
  // ...
```

Spell Checker Driver

- The main program is:

```
int main (int argc, char *argv[])
{
  if (argc != 4) {
    cerr << "usage: " << argv[0]
         << ": doc-name, main-dict, private-dict"
         << endl;
    return 1;
  }
  Spell_Checker batch_checker (argv[1], argv[2],
                               argv[3]);
  if (batch_checker.spell_check (cout) == -1)
    return -1;
  else
    return 0;
}
```

- Note how the object-oriented decomposition uses essentially the same algorithm as the original spell-checker...
  - However, the architecture is *totally* different

Advantages of Object-Oriented Design

- Increased modularity:
  1. Easier to understand the components in isolation, since data coupling and visibility have been reduced
     - *e.g.*, modules and classes are composed of related activities
  2. More adaptive to specification and implementation changes, since changes are localized
     - *e.g.*, most changes occur in representations, rather than interfaces
     - By hiding objects' representational details, changes will not ripple through design (unless class specification changes)

Advantages of Object-Oriented Design

- Class data and member functions are equally emphasized
  - However, higher-level structuring of activities is postponed
- Object behavior is independent of temporal ordering
  - *i.e.*, the *shopping list* approach
  - Easier to reuse and extend classes in other systems, since emphasis is on stable interfaces
    - *e.g.*, reuse sort from system sort application

Disadvantages of Object-Oriented Design

- Certain problem domains do not necessarily benefit from an object-oriented approach
  - *e.g.*, mathematical routines for numerical analysis, where there is no need for shared state...
- Requires more work in the upstream activities
  1. *e.g.*, analysis, modeling, and architectural design to determine architectural components, relations, and interfaces
  2. Often not as intuitive to determine the objects (without training and practice)
- Requires an object-oriented language for best results

Potential Modifications

- Make the program run interactively, rather than in "batch" mode
  - *e.g.*, integrate with a text editor and make the program work on user-selected regions of the document (*e.g.*, GNU emacs):
    1. Query the user to check if an unrecognized word is misspelled
    2. If it is misspelled then
    3. Replace the word in the document
    4. Potentially add the word to the private dictionary, if user specifies this action
    5. Produce an updated private dictionary
- Remove arbitrary limits on input document size
  - *i.e.*, does not need to fit into memory

Potential Modifications

- Make the program handle multiple input files
- Make the program handle multiple dictionaries
- Modify the program to perform other text oriented tasks, *e.g.*,
  - Build a document index or cross-referencer
  - Build an interactive thesaurus
- Make the program work on other types of files, *e.g.*,
  - LaTeX or TeX files
  - nroff files
  - MS Word files
  - postscript or dvi files

Parting Thought

- Sometimes the "best" design is the least elaborate one:

```
% cat tex-spell-check
dextex $1  | \           # strip tex formatting commands
tr A-Z a-z | \           # map upper case to lower case
tr -cs a-z '\012' | \    # remove all non-words
sort -u >! /tmp/words    # remove duplicates
                         # omit lines only in filename 2
comm -2 /tmp/words /usr/dict/words
```

- Advantage:
  - Easy to get right (once you understand UNIX tools ;-)), since it is very decoupled...
- Disadvantages
  - Doesn't work very well for prefixes/suffixes
  - Slow... (many processes, many stages)

Concluding Remarks

- Object-oriented design differs from algorithmic design in several respects:
  - Structure of the system is organized around classes/objects rather than functions
  - Objects are typically more "complete" abstractions than are functions (*e.g.*, they include data emphasis as well as control flow emphasis)
  - Algorithmically decomposed components have *verb* names, while object-oriented components have *noun* names
- Advantages of object-oriented design are most evident in
  1. *Large-scale systems*
  2. *Evolving systems*