Grammar-based Specification and Parsing for Binary File Formats

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Motivation: Digital Curation Tools

Digital Curators need automated tools for:

- **Identification of file formats**
- **Validation of file formats, with pertinent error messages**
- **Extraction of metadata**
- **Viewing/playing/reading file formats**
- **Conversion of legacy formats to current/standard formats**

Motivation: Digital Curation Tools

- **Identification: DROID/PRONOM; File/Magic**
- **Validation: Harvard's JSTOR/Harvard Object Validation Environment (JHOVE), UCDL (JHOVE2)**
- **Metadata Extractor: National Library of NZ Metadata Extractor; GNU libextractor**
- **Viewers/Players: NASAView, QuickView Plus, IrfanView, XNView, KeyView, Columbus viewer**
- **Conversion: XML Electronic Normalization of Archives (Xena), OpenOffice.org's Format Converter, Alchemy**

Motivation: Digital Curation Tools

- Almost all of these tools, especially those for binary file formats, are manually programmed from file format specifications.
- The tools become obsolete when the hardware/software platform on which the programs run becomes obsolete. The tools either need to be reprogrammed, or become unavailable.
- Need for a sustainable, more cost effective, digital preservation strategy for binary file formats.

Observation: Specification of Binary File Formats

File Layouts

0ffset	Description
0	"RIFF" 4-byte tag
4	size of data chunk starting at offset 8
8	"WEBP" the form-type signature
12	"VP8 " 4-bytes tag, describing the raw video format used
16	size of the raw VP8 image data chunk, starting at offset 20
20	the VP8 image data

C Data Structures

```
typedef struct {
        UWORD w, h;
        WORD  x, y;
        UBYTE nPlanes;
        Masking masking;
        Compression compression;
        UBYTE pad1;
        UWORD transparentColor;
        UBYTE xAspect, yAspect;
        WORD  pageWidth, pageHeight;
        } BitMapHeader;
```

Observation: Textual File Formats are Specified with Grammars

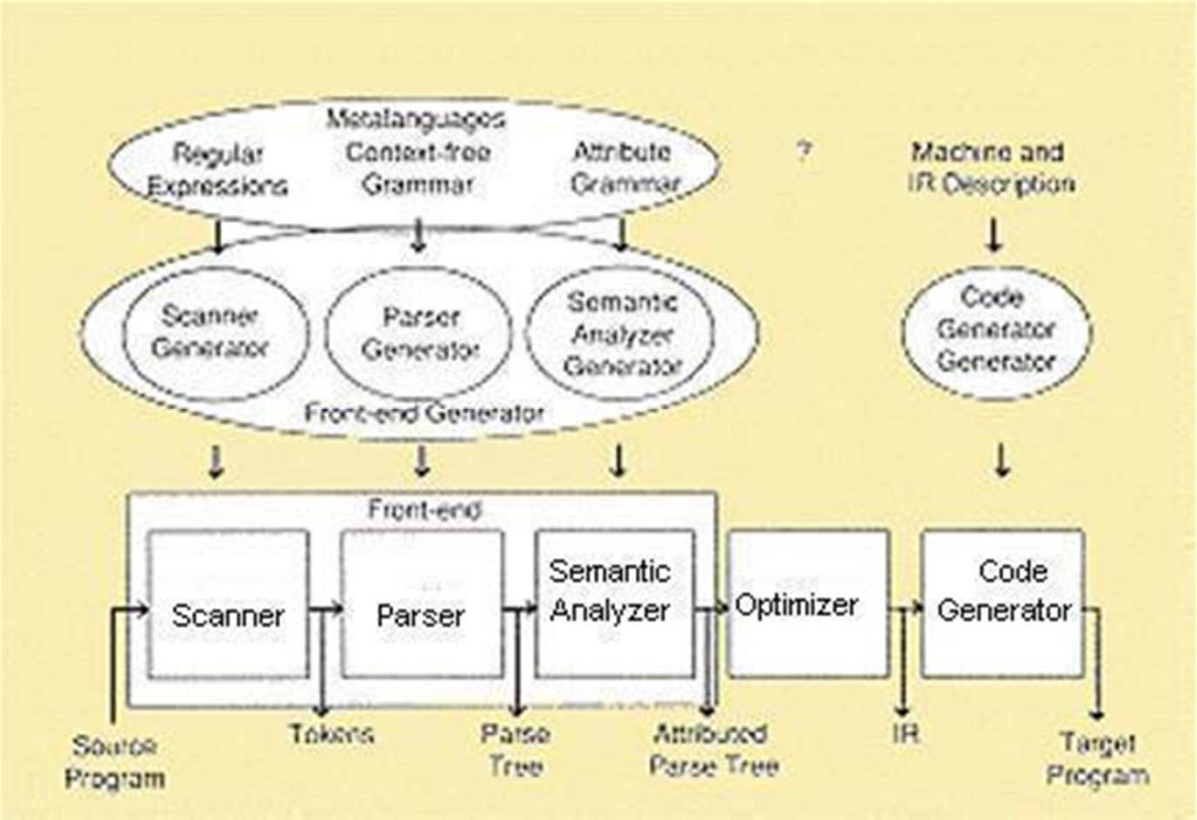
Simple Grammar for LISP Programming Language Syntax

```
expression ::= atom | list
atom ::= number | symbol
number ::= [+-]?['0'-'9']+
symbol ::= ['A'-'Z''a'-'z'].*
list ::= '(' expression* ')'
```

Scalable Vector Graphics Description of a 2D Image

```
<?xml version="1.0" standalone="no"?>
<!DOCTYPE svg PUBLIC "-//W3C//DTD SVG 1.1//EN"
"http://www.w3.org/Graphics/SVG/1.1/DTD/svg11.dtd">
<svg width="100" height="60"
     xmlns="http://www.w3.org/2000/svg">
  <rect fill="green" x="15" y="15" width="70" height="30"/>
  <rect fill="red" x="20" y="20" width="60" height="20"/>
</svg>
```

Observation: Compiler-Compiler Technology



Research Questions

- Is it possible to extend the concept of context-free grammars from textual languages to binary file formats?
- Is it possible to specify binary file formats using these extended context-free binary file grammars?
- Is it possible to create parsers from these grammars for validating file formats?
- Is it possible to develop a parser generator that takes a binary file grammar for a binary file format and generates a parser that can validate the file format?

A *context-free binary array grammar* G is a quintuple <N, D, Σ, S, P> where:

N is a finite set of non-terminal symbols,

D is a set of data types,

Σ is a finite set of binary values of data types D called terminals,

$S \in N$ is the start symbol,

P is a set of production rules of the form $N \rightarrow \{N \cup \Sigma\}^*$

Limitations of Context-free Grammars

- Context-free grammars cannot represent context-sensitive aspects of programming languages.
- They also cannot represent the semantics of programming languages, i.e., the actual computation or an interpretation in assembly language or machine language.
- Binary file formats have context-free and context-sensitive features.

Donald Knuth [1968] proposed an extension of CFGs to address the context-sensitivity and semantics of programming languages.

An *attribute grammar* AG is a triple <G, A, AR>, where:

G is a context-free grammar for the language,

A associates each grammar symbol $X \in (N \cup \Sigma)$ with a set of attributes, and

AR associates each production $R \in P$ with a set of attribute computation rules or conditions.

Kinds (Families) of Binary File Formats Based on File Structure

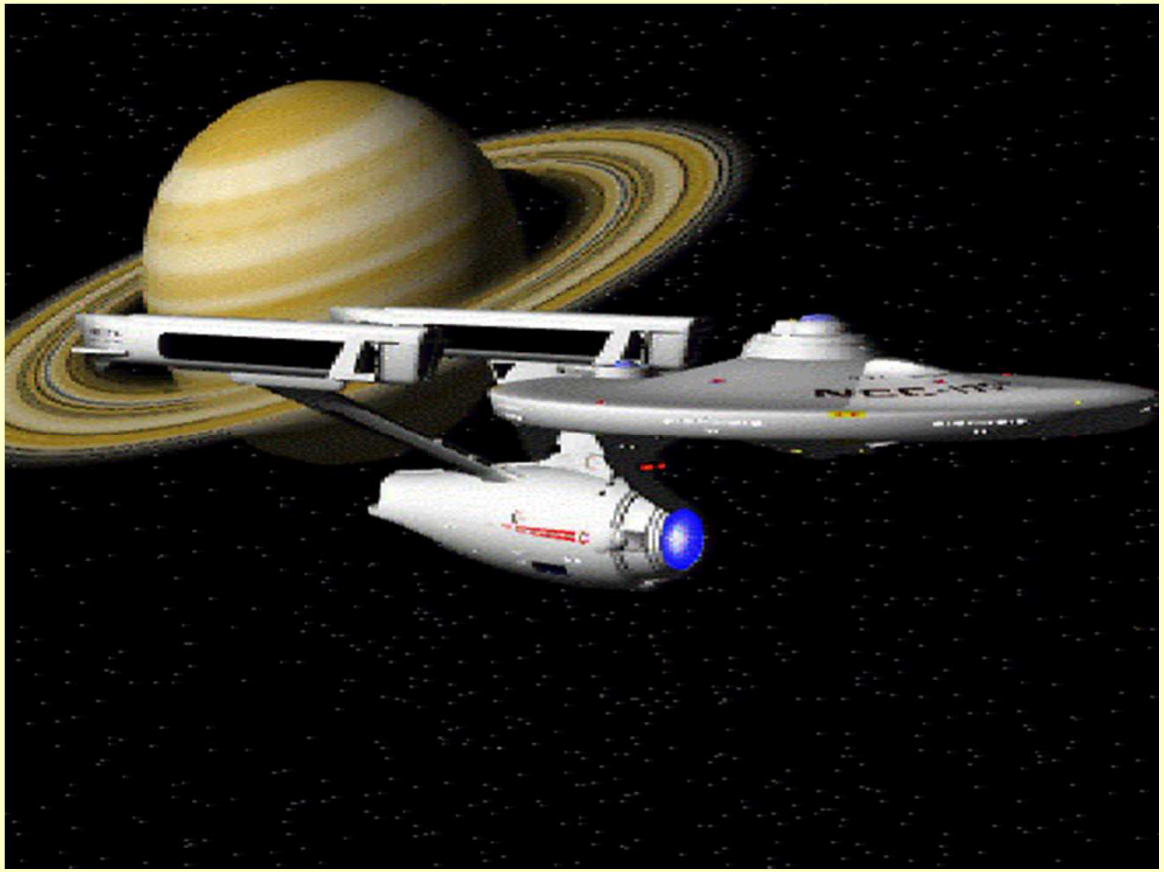
- Chunk-based
- Directory-based
- Executable
- Header-Body
- Others

Chunk-based Binary File Formats

- Interchange File Format (IFF)
- Electronic Arts & Commodore-Amiga
- A chunk consists of a chunk-id, a chunk-size and chunk-data.
- Chunk data can contain image, audio or text data. It can also contain sub-chunks and metadata.
- Sub-chunks can contain sub-sub-chunks

Chunk-based File Format Family

- Apple Audio Interchange File Format (AIFF)
- Resource Interchange File Format (RIFF) – WAV, AVI, ANI, Riff MIDIfile, Device-Independent Bitmap, Webp
- JPEG
- Advanced Systems Format – WMA, WMV
- Portable Network Graphics -- PNG, MNG, JNG
- Binary Interchange File Format (Microsoft Excel)
- 3D Studio – 3ds
- Autodesk Animator Pro – fli, flc, pic
- CorelDRAW Vector Graphics-cdw
- Apple QuickTime – mov, qt
- Structured Data Exchange Format (SDXT), and many more



Starship Enterprise Bitmap in ILBM IFF Binary File Format

Bytes 0-511 of the ILBM Binary File

```
0000:   46 4F 52 4D 00 00 C5 18 - 49 4C 42 4D 42 4D 48 44   FORM....ILBMBMHD
0010:   00 00 00 14 01 60 01 B8 - 00 00 00 00 06 00 01 80   .....`..........
0020:   00 00 0C 07 01 60 01 B8 - 41 4E 4E 4F 00 00 00 48   .....`..ANNO...H
0030:   24 56 45 52 3A 20 57 72 - 69 74 74 65 6E 20 62 79   $VER: Written by
0040:   20 41 53 44 47 27 73 20 - 41 72 74 20 44 65 70 61    ASDG's Art Depa
0050:   72 74 6D 65 6E 74 20 50 - 72 6F 66 65 73 73 69 6F   rtment Professio
0060:   6E 61 6C 20 49 46 46 33 - 2E 30 2E 34 20 28 31 39   nal IFF3.0.4 (19
0070:   2E 30 32 2E 39 35 29 00 - 43 4D 41 50 00 00 00 30   .02.95).CMAP...0
0080:   11 11 11 44 33 22 44 44 - 44 77 55 22 66 66 55 99   ...D3"DDDwU"ffU.
0090:   66 22 88 77 55 77 77 77 - AA 88 55 22 22 EE BB 99   f".wUwww..U""...
00A0:   44 99 99 AA BB AA 77 BB - BB AA DD CC AA EE EE EE   D.....w.........
00B0:   43 41 4D 47 00 00 00 04 - 00 00 08 04 44 50 49 20   CAMG........DPI
00C0:   00 00 00 04 00 96 01 01 - 42 4F 44 59 00 00 C4 50   ........BODY...P
00D0:   D5 00 F8 00 00 08 FD 00 - 00 20 FE 00 00 80 FE 00   ......... ......
00E0:   03 81 00 80 10 FA 00 02 - 01 00 08 F9 00 D5 00 D5   ................
00F0:   00 00 BF F9 FF 00 F2 FD - FF 00 CB FE FF 00 2F FE   ................/.
0100:   FF 03 2E 5F 2F E5 FA FF - 02 FE 5F F2 F9 FF 00 DF   ..._/....._.....
0110:   F9 FF 01 F3 7F FE FF 00 - CD FE FF 00 37 FE FF 03   ............7...
0120:   36 6F 37 E6 FA FF 03 FE - 6F F3 7F FA FF D5 00 FC   6o7.....o.......
0130:   00 00 20 FE 00 00 02 F9 - 00 02 20 00 01 FA 00 00   .. ....... .....
0140:   04 FC 00 00 20 FB 00 02 - 20 00 00 D5 00 D5 00 00   .... ... .......
0150:   BF FD FF 00 CB FE FF 01 - FC BF FA FF 03 CB FF FE   ................
0160:   5F FB FF 01 F9 7F FD FF - 00 CB FB FF 02 CB FF FF   _...............
0170:   00 DF FD FF 00 CD FE FF - 01 FC DF FA FF 03 CD FF   ................
0180:   FE 6F FB FF 01 F9 BF FD - FF 00 CD FB FF 02 CD FF   .o..............
0190:   FF D8 00 02 20 00 00 F8 - 00 00 08 FC 00 00 80 E5   .... ...........
01A0:   00 D5 00 D5 00 00 BF F9 - FF 00 F2 FC FF 00 2F E8   ................/.
01B0:   FF 02 CB FF FF 00 DF F9 - FF 01 F3 7F FD FF 00 37   ...............7
01C0:   E8 FF 02 CD FF FF D5 00 - D5 00 D5 00 D5 00 00 BF   ................
01D0:   D6 FF 00 DF D6 FF D5 00 - 04 00 40 00 00 08 FD 00   ..........@.....
01E0:   06 10 00 00 10 00 00 04 - F5 00 00 10 F8 00 00 04   ................
01F0:   FC 00 D5 00 D5 00 04 BF - 97 FF FF F2 FD FF 07 E5   ................
```

Binary Array Attribute Grammar for Interleaved Bitmap File Format

```
<ILBM> → "FORM" <cksize UINT32> "ILBM"
            <propertyChunk> {propertyChunk.foundBMHD==true}?
            <dataChunk><BODY>
<propertyChunk> → (<BMHD>|<CMAP>|<CAMG>)+
<BMHD> → "BMHD" <cksize UINT32>{cksize.value==20}?
            <BitmapHeader>{foundBMHD=true}
<BitMapheader> →  <width UINT32>
                  <height UINT16>
                  <xposition INT16>
                  <yposition  INT16>
                  <nplanes  BYTE>
                  <masking  BYTE>
                  <compression BYTE>
                  <reserved BYTE>
                  <transparentcolor  UINT16>
                  <xaspect BYTE>
                  <yaspect BYTE>
                  <pagewidth INT16>
                  <pageheight INT16>
<CMAP> -→"CMAP" <cksize UINT32> {cksize.value mod 3==0}? {n=cksize.val/3}
            <color>[n]
<color> → <red BYTE> <green BYTE> <blue BYTE>
<CAMG> → "CAMG" <cksize UINT32> {cksize.value==4}?
            <viewmode type=INT32>
<dataChunk> → <CRNG><CCRT>
<CRNG> → "CRNG" <cksize UINT32> <CRange>
<CCRT> →  "CCRT" <cksize UINT32> <cycleinfo>
<CRange> → <pad1, WORD> {pad1.value==0}?
            <rate, WORD> <active, WORD> <low, UBTYE> <high, UBYTE>
<cycleinfo> → <direction, WORD><start, UBYTE><end, UBYTE>
            <seconds, INT32><microseconds, INT32><pad, WORD>{pad.value==0}?
<BODY> → "BODY" <cksize UINT32> <data BYTE>[cksize.value]
```

Recursive Descent Parsers for Binary Array AttributeGrammars

Top-level Grammar Rule

<ILBM> → “FORM”

<cksize UINT32>

“ILBM”

<propertyChunk>

{propertyChunk.foundBMHD == true}?

<dataChunk>

<BODY>

Top-level Parser Function

```
private void ilbm()
{
      try
      {
            if(nextTerminal(STRING, 4).equals("FORM"))
            {
                  Long ckSize = (Long)nextTerminal(INT32).value();

                  if(nextTerminal(STRING, 4).equals("ILBM"))
                  {
                      if(propertyChunks().foundBMHD())
                      {
                        dataChunk();
                        body();
                      }
                      else
                      {
                        throw new Exception("BMHD not found");
                      }
                  }
                  else
                  {
                        throw new Exception("ILBM not found");
                  }
            }
            else
            {
                  throw new Exception("FORM not found");
            }
      }
      catch (Exception e)
      {
              e.printStackTrace();
      }
}
```

Parse Tree for ILBM File

<ILBM> : Start Symbol of the Grammar

File Signature

- **'FORM' at offset 0**
- **'ILBM' at offset 7**

<ILBM> chunk size – unsigned 32-bit integer with decimal value 50,456

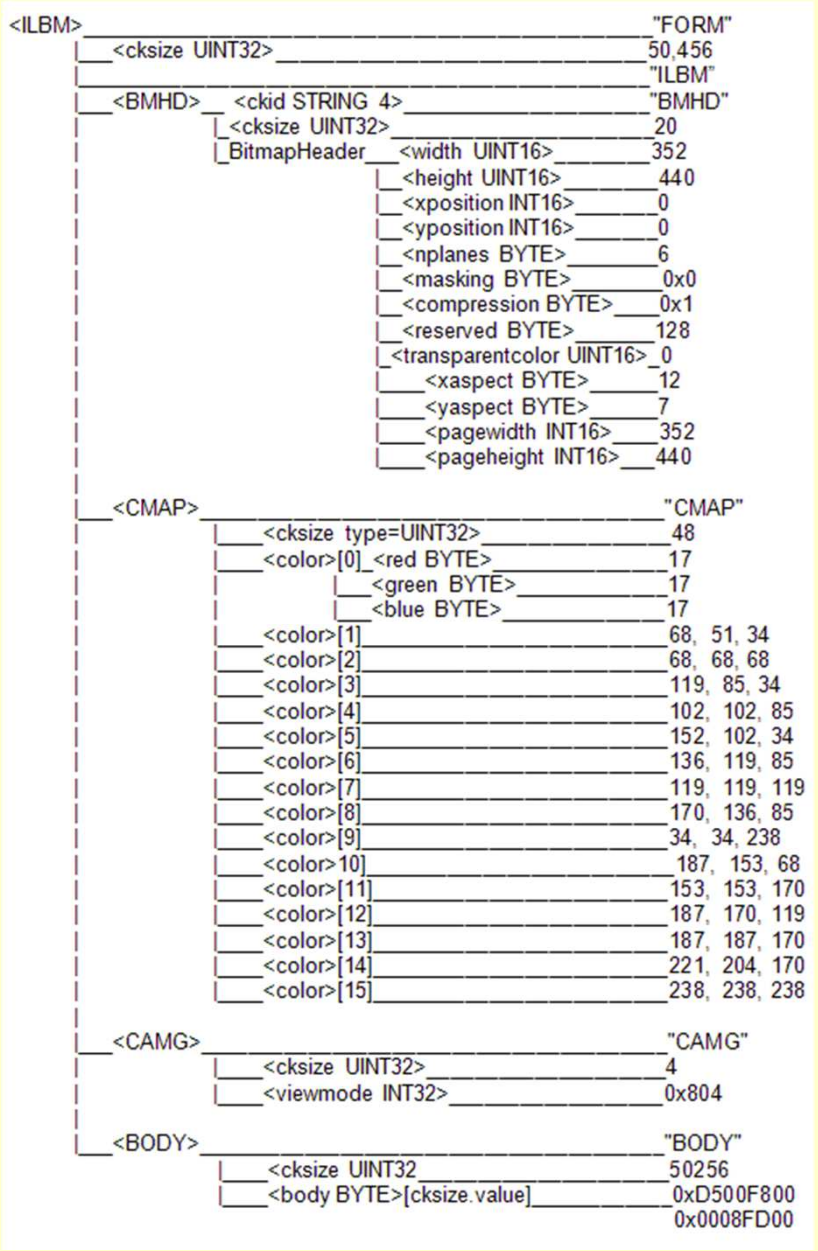
<BMHD> chunk id = 'BMHD

<BMHD> Chunk size = 20

Data chunk BitmapHeader has metadata about the Bitmap

Color pallet is stored in the <CMAP> chunk

Bitmap is stored in the <BODY> chunk.



Generating Parsers for Binary Formats

- Goal is a parser generator for binary file formats.
- ANTLR (Another Tool for language Recognition) is a parser generator
  - Input: Attribute LL(k) grammar for a string language
  - Output: Source code (e.g. Java for a recognizer of that language)
  - Wrote functions for each data type that converts character (byte) tokens to binary data types.
- Uses ANTLR to demonstrate the capability of generating parsers from file format grammars

Related Research: File Description Languages

- ASN.1 (Abstract Syntax Notation One)
- EAST/DEDSL (Extended ADA Subset / Data Entity Dictionary Specification Language)
- DATASCRIPT
- PADS/C (Processing Ad hoc Data Sources)
- DFDL (Data Format Description Language)

File Description Languages vis-a-vis Attribute Array Grammars

- Each of the data description languages described can be used to define data types and file structures of binary files.
- The binary file format grammar described in this paper most closely resembles ASN.1 and DFDL.
- The binary file grammar is the only file description language based on formal grammars that is used for creating recognizers for file formats.

Results

- It is possible to extend context-free grammars for textual languages to the specification of some chunk-based and directory-based binary file formats.
- It is possible to create parsers from these grammars for validating thse binary file formats.
- ANTLR, a parser generator for LL(k) grammars, has been successfully used to generate parsers for two chunk-based file formats and two directory-based file formats.

Further Research Questions

- Can we construct binary array attribute grammars for executable and header-body binary format families?
- Can semantics be incorporated into the grammars for binary file formats to enable the generation of viewers/players and file format converters?
- Can we construct a parser generator (a Compiler-Compiler) for binary array attribute grammars?

Further Research Questions

- Can grammar-based specifications for binary file formats be as intelligible as those that are not grammar based?
- Explicitly, how do binary array attribute grammars compare with other file description languages?
- How do we establish the correctness of the programs for validation, metadata extraction, rendering and converting file formats that are generated from attribute grammar specifications and a compiler/compiler?

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