B4M36ESW: Efficient software

Lecture 7: Data structure serialization, RPC

Michal Sojka
michal.sojka@cvut.cz

CZECH TECHNICAL UNIVERSITY IN PRAGUE

April 16, 2018

Outline

1. Introduction
2. Less efficient data serialization
   - XML
   - JSON
3. Faster alternative (C/C++)
4. Data serialization “frameworks”
   - CORBA
   - Protobufs
   - Cap’n’proto
   - Apache Avro

Outline

Communication between programs

- Over network
  - Communication protocol (e.g. over TCP)
  - Structured data serialization (JSON, protobufs, ...)
  - Remote Procedure Call (RPC)
    1. Serialize procedure name and arguments
    2. Send request and wait for response
    3. Deserialize reponse
  - Remote Method Invocation (RMI)
    - Almost the same as RPC
- On local host
  - Single address space (threads)
    - Data structures in memory
    - Language type system helps you to avoid mistakes!
  - Different address spaces (processes)
    - Same as “over network”
    - Ideally zero-copy via shared memory

Outline

Outline

XML

- eXtensible Markup Language

```xml
<employees>
    <employee>
        <firstName>John</firstName> <lastName>Doe</lastName>
    </employee>
    <employee>
        <firstName>Anna</firstName> <lastName>Smith</lastName>
    </employee>
    <employee>
        <firstName>Peter</firstName> <lastName>Jones</lastName>
    </employee>
</employees>
```

- Very high overhead (both size and computation)
- Complex parser

Outline

JSON

- JavaScript Object Notation

```
{"employees":[
    { "firstName":"John", "lastName":"Doe" },
    { "firstName":"Anna", "lastName":"Smith" },
    { "firstName":"Peter", "lastName":"Jones" }
]}
```

- lower overhead, simpler parser

json-c parser

https://github.com/json-c/json-c

```c
#include <json.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
  struct json_tokener *tok = json_tokener_new();
  char buf[1024*1024];
  struct json_object *jobj;

  FILE *f = fopen("test.json", "r");

  do {
    size_t len = fread(buf, 1, sizeof(buf), f);
    jobj = json_tokener_parse_ex(tok, buf, len);
  } while (json_tokener_get_error(tok) == json_tokener_continue);
  fclose(f);
  return 0;
}
```

Profiling json-c

47 MB JSON file

- `perf stat ./bench-json-c`

```
 Performance counter stats for './bench-json-c':

       3001.802390      task-clock (msec)         #    0.974 CPUs utilized
               412      context-switches          #    0.137 K/sec
                 5      cpu-migrations            #    0.002 K/sec
           478,891      page-faults               #    0.160 M/sec
     9,368,533,705      cycles                    #    3.121 GHz
     3,377,028,216      stalled-cycles-frontend   #   36.05% frontend cycles idle
    14,910,459,852      instructions              #    1.59  insn per cycle
                                                  #    0.23  stalled cycles per insn
     3,144,829,442      branches                  # 1047.647 M/sec
        31,808,151      branch-misses             #    1.01% of all branches

       3.082290868 seconds time elapsed
```

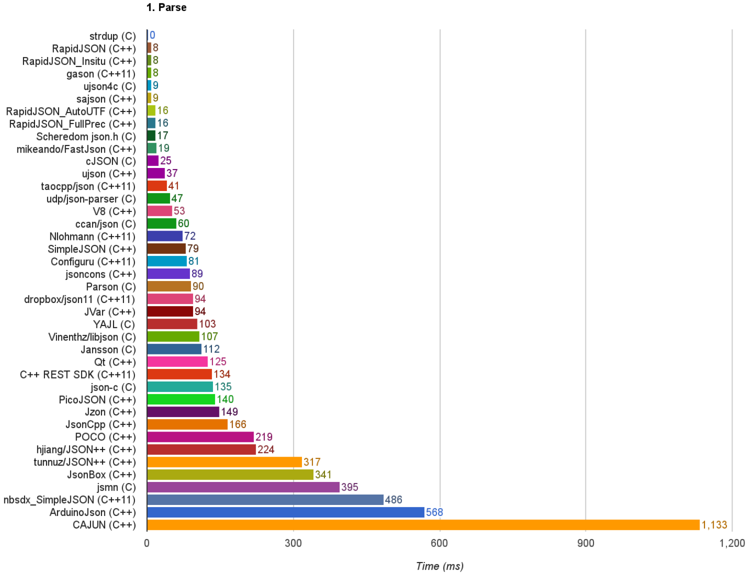
- `perf record --freq 10000 -e cycles ./bench-json-c`

```
 21.28%  bench-json-c  bench-json-c       [.] json_tokener_parse_ex
 10.67%  bench-json-c  bench-json-c       [.] _int_malloc
  9.28%  bench-json-c  bench-json-c       [.] _IO_vfscanf_internal
  4.30%  bench-json-c  bench-json-c       [.] __libc_calloc
  3.37%  bench-json-c  bench-json-c       [.] ____strtod_l_internal
  3.30%  bench-json-c  bench-json-c       [.] __memset_sse2_unaligned_erms
  3.05%  bench-json-c  [kernel.kallsyms]  [k] clear_page_c_e
  2.60%  bench-json-c  [kernel.kallsyms]  [k] page_fault
```

Where is time spent in `json_tokener_parse_ex`?

```
       |              while (isspace((int)c)) {
  0.21 |          movsbq %dl,%rax
  0.07 |          testb  $0x20,0x1(%rcx,%rax,2)
  7.08 |        ↓ je     361
  0.29 |          xchg   %ax,%ax
       |                 if ((!ADVANCE_CHAR(str, tok)) || (!PEEK_
  0.02 | 330:     mov    0x20(%rbx),%eax
```

JSON benchmark



Trying RapidJSON

- bench-rapidjson.cpp

```
#include <rapidjson/document.h>
#include <rapidjson/filereadstream.h>
using namespace rapidjson;

int main(int argc, char *argv[]) {
  FILE* fp = fopen("test.json", "r");
  char readBuffer[1024*1024];
  FileReadStream is(fp, readBuffer, sizeof(readBuffer));
  Document d;
  d.ParseStream(is);
  fclose(fp);
  return 0;
}
```

- perf stat bench-rapidjson

```
 Performance counter stats for './bench-rapidjson':

        389.890403      task-clock (msec)         #    0.998 CPUs utilized
                12      context-switches          #    0.031 K/sec
                 0      cpu-migrations            #    0.000 K/sec
            43,392      page-faults               #    0.111 M/sec
     1,106,686,422      cycles                    #    2.838 GHz
       206,781,432      stalled-cycles-frontend   #   18.68% frontend cycles idle
     2,467,762,722      instructions              #    2.23  insn per cycle
                                                  #    0.08  stalled cycles per insn
       593,437,567      branches                  # 1522.063 M/sec
            61,403      branch-misses             #    0.01% of all branches

       0.390790908 seconds time elapsed
```

What about spaces?

- perf record/report

```
23.66%  bench-rapidjson     [.] rapidjson::GenericReader<...>::ParseString<0u, ra...
22.43%  bench-rapidjson     [.] rapidjson::GenericReader<...>::ParseValue<0u, rap...
18.94%  bench-rapidjson     [.] rapidjson::GenericReader<...>::ParseNumber<0u, ra...
11.66%  bench-rapidjson     [.] rapidjson::SkipWhitespace<rapidjson::FileReadStream>
 5.70%  libc-2.24.so        [.] __memmove_sse2_unaligned_erms
 2.75%  bench-rapidjson     [.] rapidjson::GenericDocument<rapidjson::UTF8<char>, rapidjson::MemoryPool
 1.96%  [kernel.kallsyms]   [k] page_fault
 1.68%  [kernel.kallsyms]   [k] clear_page_c_e
```

- perf annotate rapidjson::GenericReader<...>::ParseString...

```
       |                 Ch c = is.Peek();
       |                 if (RAPIDJSON_UNLIKELY(c == '\\')) {    // Escape
 12.22 |  96:   cmp     $0x5c,%r14b
       |      ↓ je      178
       |                         TEncoding::Encode(os, codepoint);
       |                     }
       |                     else
       |                         RAPIDJSON_PARSE_ERROR(kParseErrorStringEscapeInvalid, escapeOffset);
       |                 }
       |                 else if (RAPIDJSON_UNLIKELY(c == '"')) {    // Closing double quote
  6.01 |        cmp     $0x22,%r14b
       |      ↓ je      200
       |                     is.Take();
       |                     os.Put('\0');    // null-terminate the string
       |                     return;
       |                 }
```

- What is RAPIDJSON_UNLIKELY?
  Branch predition hint (see __builtin_expect() in gcc manual)

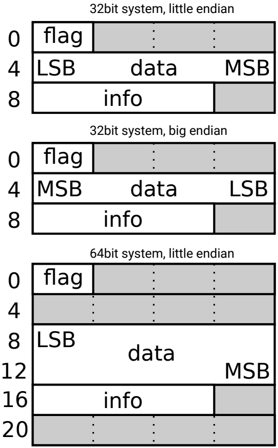
Outline

Raw memory

- Sending/receiving directly the content of memory:

```
struct data {
        char flag;
        long int data;
        char info[3];
};

void sendData(struct data &d) {
        send(sock, &d, sizeof(d));
}
void recvData(struct data &d) {
        recv(sock, &d, sizeof(d));
}
```



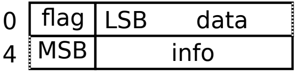
Raw memory

Problems & solutions

- type size ⇒ `#include <stdint.h>` ⇒ `int32_t`
- endianing ⇒ `#include <endian.h>` ⇒ `htole32()` etc.
  (host to little-endian 32 bits)
- padding ⇒ `__attribute__((__packed__))`

- ```
  struct __attribute__ ((__packed__)) data {
          char flag;
          int32_t data;
          char info[3];
  };

  void recvData(struct data &d) {
          struct data dd;
          recv(sock, &dd, sizeof(dd));
          d = dd;
          d.data = htole32(dd.data);
  }
  ```


  ```

Raw memory

Properties

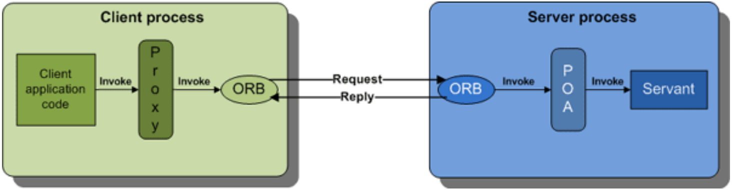
- Blazingly fast, but inflexible
- Receive side must know the format of data
  - What if sender has newer version than receiver?
    - e.g. field added/removed, type changed
  - Versioning of the protocol!

Outline

Outline

Common Object Request Broker Architecture (CORBA)

- Language independent “RPC framework” from ’90
- Interface Description Language (IDL)
- Automatic generation of (de)serialization code (IDL compiler)
- Description of data structure is not normally sent with the data
- CORBA is not very popular today, perhaps because of its complexity and difficulty of using parts of it (such as CDR) independently



Interface Description Language (IDL)

- In different frameworks called “schema”
- Defines only data types and interfaces
- IDL compiler generates corresponding definitions in target language as well as conversion code to/from the CDR form.
- Example:

```
module Finance {
  typedef sequence<string> StringSeq;
  struct AccountDetails {
    string     name;
    StringSeq  address;
    long       account_number;
    double     current_balance;
  };
  exception insufficientFunds { };
  interface Account {
    void deposit(in double amount);
    void withdraw(in double amount) raises(insufficientFunds);
    readonly attribute AccountDetails details;
  };
};
```

Common Data Representation (CDR)

- Endian
  - Data is sent in sender’s endian
  - Message header specifies, which endian it is $\Rightarrow$ no expensive endian conversion between similar hosts
- Data padding as in memory – efficient (de)serialization
- TypeCodes – CDR representation of any IDL data type
  - Allows to send Any data type (TypeCode + actual data) and receiver can reconstruct it

Outline

Google Protocol Buffers (protobufs)

https://developers.google.com/protocol-buffers/

- Data description – conceptually similar to IDL
- Automatic code generation
- Partial description of data sent with the data
  - Less porblems with protocol versioning
- Easy to use API
- Supports multiple languages: Java, Python, C++, C#, …

```
syntax = "proto3";

message SearchRequest {
  string query = 1;
  int32 page_number = 2;
  int32 result_per_page = 3;
}
```

- Numbered “tags” uniquely identify fields.

Wire encoding

- Key-value pairs
- Key = the tag + type information
- Unknown key-values can always be skipped
- Key: `(field_number << 3) | wire_type` (stored as varint)

Type	Meaning	Used For
0	Varint	int32, int64, uint32, uint64, sint32, sint64, bool, enum
1	64-bit	fixed64, sfixed64, double
2	Length-delimited	string, bytes, embedded messages, packed repeated fields
3	Start group	groups (deprecated)
4	End group	groups (deprecated)
5	32-bit	fixed32, sfixed32, float

Wire encoding – Varint

- Encoded in variable number of bytes, small numbers take only one byte
- 7th bit is 1 in all but last byte.
- Bits 0–6 store the value.
- 9 = 0000 0101b $\rightarrow$ 0000 0101b
- 300 = 1 0010 1100b $\rightarrow$ 1010 1100 0000 0010
- Signed integers (sint) use ZigZag encoding:
  - `(n << 1) ^ (n >> 31)`
  - 0 $\rightarrow$ 0, -1 $\rightarrow$ 1, 1 $\rightarrow$ 2, -2 $\rightarrow$ 3, …

Wire encoding – String and Message

- Varint-encoded length + bytes of string/message
- ```
  message Test2 {
    required string b = 6;
  }
  ```
- b = “testing”
  - 32 07 74 65 73 74 69 6e 67
  - 32h = `(6 << 3) | 2`
  ```

Wire encoding – repeated fields

- ```
  message Test4 {
    repeated int32 d = 4 [packed=true];
  }
  ```
- ```
  22        // tag (field number 4, wire type 2)
  06        // payload size (6 bytes)
  03        // first element (varint 3)
  8E 02     // second element (varint 270)
  9E A7 05  // third element (varint 86942)
  ```

Message streaming

- Parsing code does not know where a message begins and ends
- Put the length of the message before it

Protobuf example – OpenStreetMap

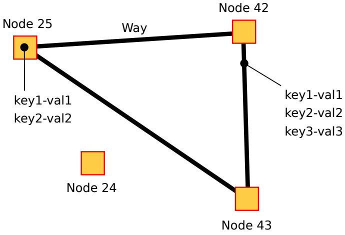
https://wiki.openstreetmap.org/wiki/PBF_Format

```
message Node {
  required sint64 id = 1;
  // Parallel arrays.
  repeated uint32 keys = 2 [packed = true]; // String IDs.
  repeated uint32 vals = 3 [packed = true]; // String IDs.
  optional Info info = 4; // May be omitted in omitmeta
  required sint64 lat = 8;
  required sint64 lon = 9;
}

message Way {
   required int64 id = 1;
   // Parallel arrays.
   repeated uint32 keys = 2 [packed = true];
   repeated uint32 vals = 3 [packed = true];

   optional Info info = 4;

   repeated sint64 refs = 8 [packed = true];  // DELTA coded
}
```



Czech republic: PBF – 670 MB, XML – 16 GB

From .proto to C++

```
package tutorial;

message Person {
  required string name = 1;
  required int32 id = 2;
  optional string email = 3;

  enum PhoneType {
    MOBILE = 0;
    HOME = 1;
    WORK = 2;
  }

  message PhoneNumber {
    required string number = 1;
    optional PhoneType type = 2 [default = HOME];
  }

  repeated PhoneNumber phones = 4;
}

message AddressBook {
  repeated Person people = 1;
}
```

```
#include <iostream>
#include <fstream>
#include <string>
#include "addressbook.pb.h" // generated from .proto
using namespace std;

// Iterates though all people in the AddressBook and prints info about them
void ListPeople(const tutorial::AddressBook& address_book) {
  for (int i = 0; i < address_book.person_size(); i++) {
    const tutorial::Person& person = address_book.person(i);

    cout << "Person ID: " << person.id() << endl;
    cout << "  Name: " << person.name() << endl;
    if (person.has_email()) {
      cout << "  E-mail address: " << person.email() << endl;
    }

    for (int j = 0; j < person.phone_size(); j++) {
      const tutorial::Person::PhoneNumber& phone_number = person.phones(j);

      switch (phone_number.type()) {
        case tutorial::Person::MOBILE:
          cout << "  Mobile phone #: ";
          break;
        case tutorial::Person::HOME:
          cout << "  Home phone #: ";
          break;
        case tutorial::Person::WORK:
          cout << "  Work phone #: ";
          break;
      }
      cout << phone_number.number() << endl;
    }
```

Outline

Cap’n’proto

`https://capnproto.org/`

- Developed by the original author of protobufs
- Some years later – lessons learnt from protobufs
- Very efficient for communication via shared memory (e.g. between different languages)
- Still usable over network
- No de/encoding needed – serialized form is usable as native form (if packing is not in use)

Cap’n’proto encoding

- Bool: 1 bit
- Integers: Little endian, native size, aligned to multiple of their size (padding)
- Default values: always encoded as zero, i.e.

  `enc = val ^ default`
- Optional packing = getting rid of zero bytes
  - Set bits in the first byte indicate which of the following 8 bytes are non-zero. The nonzero bytes follow.
  - ```
    unpacked (hex):  08 00 00 00 03 00 02 00  19 00 00 00 aa 01 00 00
    packed (hex):  51 08 03 02   31 19 aa 01
    ```
- Structures: Pointer (= index) to data and sub-structures
    ```

Message + structure encoding

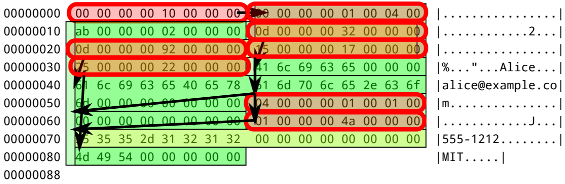
https://capnproto.org/encoding.html

```
struct Person {
  id @0 :UInt32;   # 0xab
  name @1 :Text;   # Alice
  email @2 :Text; # alice@example.com
  phones @3 :List(PhoneNumber);

  struct PhoneNumber {
    number @0 :Text; # "555-1212"
    type @1 :Type;    # mobile

    enum Type {
      mobile @0;
      home @1;
      work @2;
    }
  }

  employment :union {
    unemployed @4 :Void;
    employer @5 :Text;
    school @6 :Text; # MIT
    selfEmployed @7 :Void;
  }
}
```



- Tree-like data structure. Allows skipping of unknown or unwanted data.
- Packing allows getting rid of all zero bytes above and adds 17 more bytes.

From .capnp to C++

```
struct Person {
  id @0 :UInt32;
  name @1 :Text;
  email @2 :Text;
  phones @3 :List(PhoneNumber);

  struct PhoneNumber {
    number @0 :Text;
    type @1 :Type;

    enum Type {
      mobile @0;
      home @1;
      work @2;
    }
  }

  employment :union {
    unemployed @4 :Void;
    employer @5 :Text;
    school @6 :Text;
    selfEmployed @7 :Void;
    # We assume that a person is only one of these.
  }
}

struct AddressBook {
  people @0 :List(Person);
}
```

```
#include "addressbook.capnp.h"
#include <capnp/message.h>
#include <capnp/serialize-packed.h>
#include <iostream>

void printAddressBook(int fd) {
  ::capnp::PackedFdMessageReader message(fd);

  AddressBook::Reader addressBook = message.getRoot<AddressBook>();

  for (Person::Reader person : addressBook.getPeople()) {
    std::cout << person.getName().cStr() << ": "
              << person.getEmail().cStr() << std::endl;
    for (Person::PhoneNumber::Reader phone: person.getPhones()) {
      const char* typeName = "UNKNOWN";
      switch (phone.getType()) {
        case Person::PhoneNumber::Type::MOBILE: typeName = "mobile"; break;
        case Person::PhoneNumber::Type::HOME: typeName = "home"; break;
        case Person::PhoneNumber::Type::WORK: typeName = "work"; break;
      }
      std::cout << "  " << typeName << " phone: "
                << phone.getNumber().cStr() << std::endl;
    }
    Person::Employment::Reader employment = person.getEmployment();
    switch (employment.which()) {
      case Person::Employment::UNEMPLOYED:
        std::cout << "  unemployed" << std::endl;
        break;
      case Person::Employment::EMPLOYER:
        std::cout << "  employer: "
                  << employment.getEmployer().cStr() << std::endl;
        break;
      case Person::Employment::SCHOOL:
```

Outline

Apache Avro

- Schema in JSON
- Schema handshake after connection establishment
- No tags in data, because schema is known to all parties
- File storage
  - Compression
  - Blocks allowing skip through the data without deserialization