Concurrent Systems

Nebenläufige Systeme

V. Elementary Operations

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November 11, 2015

Agenda

Outline

Subject Matter

- discussion on **abstract concepts** as to elementary operations at instruction structure set architecture level
  - atomic load/store of a naturally aligned machine word
  - atomic read-modify-write of complex machine instructions

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  - atomicity, visibility, and ordering of memory operations against the background of UMA, NUMA, and (partly) COMA architectures
  - ordering enforcing hardware such as memory barriers or fences, resp., allowing one to pattern sequential, relaxed, and weak **data consistency**

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  - ordering enforcing hardware such as memory barriers or fences, resp., allowing one to pattern sequential, relaxed, and weak **data consistency**
- excursion into practice of **hardware features** that are of importance for the implementation of any synchronisation algorithm

Outline

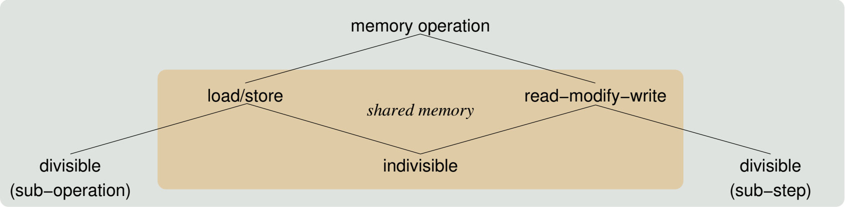
Preface

Primitive Instructions
- Atomic Operations
- Equivalence

Memory Models
- Properties

Summary

Memory-Operation Semantics



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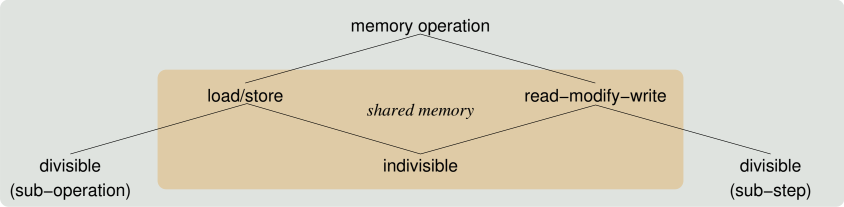

- of particular interest (at this point) are **shared-memory operations**
  - commonality is the opportunity, at least, for **indivisible execution**
- note, all memory operations are also divisible in the following respect:

sub-operation
- processors are word-oriented, but memory is byte-oriented
- with *word size* as a multiple of *byte size*, e.g. 4×8 bits
- thus, loads/stores will operate on a **sequence of bytes**

sub-step
- processors perform a *fetch-execute-cycle* to run programs
- n-address machines mean n-operand instructions, $n \geq 2$ [1]
- thus, execution requires a **sequence of loads/stores**

[1] In general $n \geq 0$, but only for $n \geq 2$ becomes the problem apparent.

Load/Store I

```c
#include <stdint.h>

static int64_t label;

int64_t get_label() {
    return label;
}

void set_label(int64_t value) {
    label = value;
}
```

Load/Store I


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3  static int64_t label;
4
5  int64_t get_label() {
6      return label;
7  }
8
9  void set_label(int64_t value) {
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11 }
```

- in logical respect any of these single statements is indivisible, atomic
  - lines 6 conceals a load and line 10 conceals a store operation
  - each case forms an ELOP of the **abstract processor** “C”

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  - lines 6 conceals a load and line 10 conceals a store operation
  - each case forms an ELOP of the **abstract processor** “C”
- in physical respect these statements are **conditionally atomic**, only
  - a matter of optimisation options, the CPU, and alignment restrictions

Load/Store II

gcc -m32...

```
get_label:
  movl label, %eax
  movl label+4, %edx
  ret

set_label:
  movl 4(%esp), %eax
  movl 8(%esp), %ecx
  movl %ecx, label+4
  movl %eax, label
  ret
```

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gcc -m64...

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get_label:
  movq label(%rip), %rax
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  movq %rdi, label(%rip)
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- any of these 8 `mov` instructions is **conditionally indivisible**

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- beware of the processor architecture or the data alignment, resp.
  - usually, memory-word loads/stores are indivisible if “word” corresponds to the smallest addressable unit of main memory: **byte**, nowadays
  - on some architectures (e.g., x86) they are indivisible too if the address of the memory operand is ***naturally aligned***

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    - reusable hardware resource, shareable, allocated per (load/store) step
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  - while the loads/stores may be in sync, the compound action is not
- indivisibility requires a **bus lock** for the duration of the whole cycle:
  - i an **atomic RMW instruction** that implicitly performs the lock *or*
  - ii a **lock prefix** that makes the adjacent normal RMW instruction atomic

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Test & Set I

Definition (TS, acc. IBM System/370)

The leftmost bit (bit position 0) of the byte located at the second-operand address is used to set the condition code, and then the entire addressed byte is set to all ones. [8, p. 144]

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- the operation effectly does an **unconditional store** in main memory
  - *The byte in storage is set to all ones as it is fetched for the testing of bit position 0. [8, p. 144]* [3]

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```
bool tas(byte *ref) {
  atomic { bool aux = *ref & 0x1; *ref = 0x11111111; }
  return aux;
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  - with first and second operand being used to form effective address *ref*

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int tas(any_t *ref) {
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tas:
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  - note that `xchg` interlocks against simultaneous main memory accesses
- beware of the unconditional store carried out by both `TS` and `xchg`[4]
  - this semantic has a **deleterious effect** for cache-coherent processors
  - the cache line holding the main memory operand is always invalidated

↪ dedicated hardware implementation (p. 12) or mapping to CAS (p. 13)

[4] Same holds for `TAS` of the M68000 family and `ldstub` of the SPARC family.

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Definition (Dual-Ported RAM)

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  - records the processor that issued the TAS and acquired access
  - notifies processors that, at a time, issue a TAS simultaneously
    - signalling *BUSY* interrupt, forcing the receiving processor into **busy waiting**
  - performs the test and then, if and only if the test succeeds:
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- this scheme translates into a **conditional store** as follows:

```
word tas(word *ref) {
  word aux;
  atomic { if ((aux = *ref) == 0) *ref = 1; }
  return aux;
}
```

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*The ABA problem is a **false positive** execution of a CAS-based speculation on a shared location L_i. [2, p. 186]*

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  - i that the two operands subject to comparison are equal and, thus, purport the presence of a certain condition (*positive*),
  - ii but the condition is not in fact present (*false*)

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  - value A read by P_1 from L_i be a sign of a dedicated global state S_1, but P_1 will be delayed before being able to commit a new value to L_i
  - meanwhile P_2 changes the value of L_i to B and then back to A, defining a new global state $S_2 \neq S_1$
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- severity of false positive execution depends on the problem (cf. p. 36)

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Paired instructions to form a flow of actions without any guarantee of indivisibility but that it succeeds only in case of indivisible operation.

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- makes a **reservation** on that very address (range)[5]

`SC`
- checks for a reservation on the specified effective memory address[5]
- if the reservation persists, stores the specified word at that address
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  ii execution of `LL` by another processor applying the same address (range)

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- `LL` and `SC` interlock against simultaneous main memory accesses

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Load-Linked/Store-Conditional II

- use of LL/SC to recreate TAS and CAS:
  - in case of TAS, a boolean variable is conditionally set true

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int tas(long *ref) {
    return (LL(ref) == 0) && SC(ref, 1);
}
```

  - in case of CAS, a memory word is conditionally overwritten ?!

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int cas(long *ref, long old, long new) {
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- note that this implementation of CAS is free from the ABA problem:

P_1
- shares location *ref* with P_2, established reservation ref_{P_1} by LL
- gets delayed for some reason, thus has not yet executed SC

P_2
- overlaps P_1, establishes reservation ref_{P_2} and, thus, cancels ref_{P_1}
- successfully executes SC $\Rightarrow$ CAS succeeds

P_1
- resumes $\Rightarrow$ SC will fail because reservation ref_{P_1} is invalid
- returns failure of CAS $\Rightarrow$ rolls back, backs up, and retries CAS. . .

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    prefix – save the old value of G for return, then add L to G

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  - whereby (cf. p. 39):

$$FAA(G, L) \equiv AAF(G, L) - L \quad \text{and}$$
$$AAF(G, L) \equiv FAA(G, L) + L$$

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$$
\begin{aligned}
FAA(G, L) &\equiv AAF(G, L) - L \quad \text{and} \\
AAF(G, L) &\equiv FAA(G, L) + L
\end{aligned}
$$

- transferable to any associative binary operation *fetch-and-Φ*
  - but for noninvertible operations the prefix form is considered more general
  - be $\Phi = max$ (i.e., X): only $XAF(G, L) \equiv max(FAX(G, L), L)$ (cf. p. 40)

Equality of Atomic Operations

- operations that need consensus number n cannot have a semantically equivalent implementation by operations of consensus number $m < n$

Definition (Consensus Number)

The consensus number for X *is the largest* n *for which* X *solves* n*-process consensus. If no largest* n *exists, the consensus number is said to be infinite. [7, p. 130]*

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- key point is the **progress guarantee** a certain operation has to give
  - for wait-freedom [7], the operation must have consensus number $n = \infty$
  - in that case, every action has guarantee to complete in finite steps/time

Outline

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  - visibility depends on the memory architecture, may cause "jitter"
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- as to the level of abstraction, they must all be considered together
  - this is especially true for the operating-system machine level (i.e., level 3)

Atomicity

- common are two classes of memory-sensitive operations (cf. p. 25):

  L/S
  - atomic load (L) or store (S), resp., as single action
  - granularity is the **machine word**, i.e., a multiple of a byte
  - with **word-alignment** constraint on the operand address, usually
    - only word-aligned accesses will be carried out indivisibly

  RMW
  - atomic read (R), modify (M), and write (W) as single action
  - common for CISC and, there, for **two-address machines**
    - uncommon for RISC, which is characteristic of load/store principle
  - single- or double-word cycles for 32- or 64-bit architectures, resp.
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    - i.e.: `CDS` or `cmpxchg8b`/`cmpxchg16b` compared to DCAS or `CAS2`
- processes cannot observe any intermediate steps and partial effects
  - here, only in matters of a single (L/S or RMW) machine instruction
  - that is to say, the ISA-level action appears ***indivisible*** and ***irreducible***
  - as a consequence, the instruction will be performed entirely or not all
    - with the latter meaning *failure indication* (TAS, CAS, SC)

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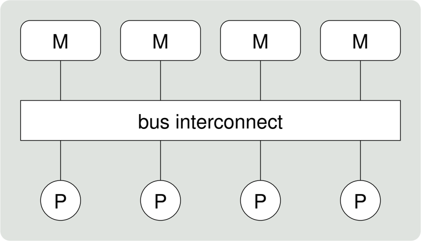
- orthogonal with it is the **consistency** aspect as to shared information stored in multiple local **caches**
  - *cache-coherent* (cc) v. *non-cache-coherent* (ncc) memory architecture

Memory Architectures at a Glance

UMA (*symmetric multiprocessing*, SMP)



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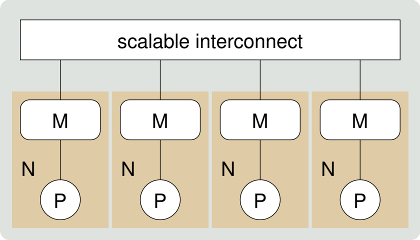

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  - zone of uniform memory characteristic
- NUMA distance
  - number of (network) hops to distant memory

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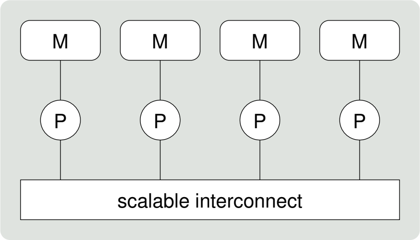

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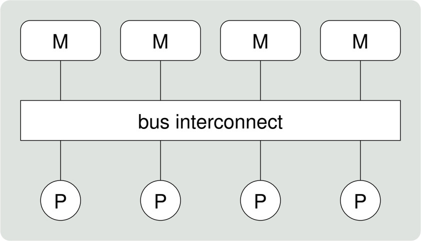

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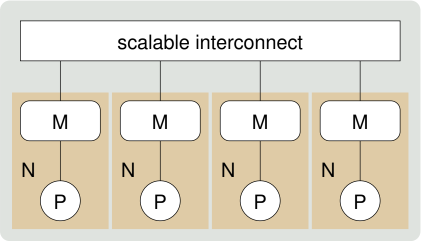

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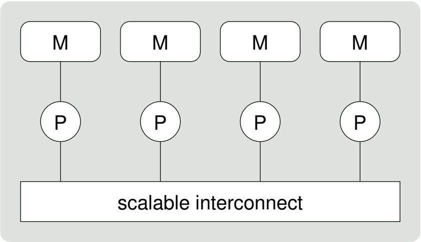

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  - on the other hand, the CPU reorders ($L2$) instructions[6] at run-time
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- ordering ensuring needs special instructions: **memory barrier/fence**

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Dynamic Ordering

- assuming that the following function is executed by a single processor, but the global variables are then read by at least one more processor:

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1 int a = 1, b = 2;
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3 void ab_set() {
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- what values of *a* and *b* are delivered?
  - line 8 may read the *new* value of *b* while line 9 may read the *old* value of *a*
  - although the assignment to *a* (line 4) was instructed previous to the one of *b*

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Memory barrier instructions directly control only the interaction of a CPU with its cache, with its write-buffer that holds stores waiting to be flushed to memory, and/or its buffer of waiting loads or speculatively executed instructions. [12]

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- CAS and LL/SC typically include a `StoreLoad` barrier on the target
  - i.e., not only a general-purpose but also the most expensive fence

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- **data consistency** as close as possible to sequential processes or with optimisation margins for high-latency memory

sequential
- processors see writes on the same target in the same order
- but the order may appear different for an "external observer"[8]
- two requirements: **program order** and **write atomicity** [11]

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- "limited to hardware-recognized synchronizing variables" [4]
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Résumé

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  - atomic load/store of a naturally aligned machine (double-) word
  - atomic read-modify-write of complex machine instructions
    - TAS, CAS and FAA or FAΦ, resp., for CISC and LL/SC for RISC
  - equality of atomic operations as to their **consensus number**
- memory-access properties that are relevant to multi-threading
  - atomicity, visibility, and ordering of memory operations
  - memory architectures of type UMA, NUMA, and COMA
  - **dynamic ordering** at instruction set architecture level
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- **hardware features** that are of importance for the implementation of any synchronisation algorithm
  - including but not limited to non-blocking synchronisation, especially

Résumé

- elementary operations at instruction structure set architecture level
  - atomic load/store of a naturally aligned machine (double-) word
  - atomic read-modify-write of complex machine instructions
    - TAS, CAS and FAA or FAΦ, resp., for CISC and LL/SC for RISC
  - equality of atomic operations as to their **consensus number**
- memory-access properties that are relevant to multi-threading
  - atomicity, visibility, and ordering of memory operations
  - memory architectures of type UMA, NUMA, and COMA
  - **dynamic ordering** at instruction set architecture level
  - memory barriers or fences, resp., to enforce ordering proper
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- **hardware features** that are of importance for the implementation of any synchronisation algorithm
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Unconditional Store: Workaround

- "textbook semantics" of TAS has a **deleterious effect** for the cache:

```
word tas(word *ref) {
  atomic { word aux = *ref; *ref = 1; }
  return aux;
}
```

  - same is true when using the GCC atomic built-in function (x86, cf. p 11):

```
#define TAS(ref) __sync_lock_test_and_set(ref, 1)
```

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```
#define TAS(ref) __sync_lock_test_and_set(ref, 1)
```

- use of CAS, with `#define CAS __sync_bool_compare_and_swap`

```
int tas(long *ref) {
  return CAS(ref, 0, 1);
}
```

  - worst-case overhead of five instructions (cf. p 11)
  - pays off, depending on processor and cache architecture

```
tas:
  xorl      %eax, %eax
  movl      $1, %ecx
  movl      4(%esp), %edx
  lock
  cmpxchgl  %ecx, (%edx)
  testl     %eax, %eax
  sete      %al
  movzbl    %al, %eax
  ret
```

ABA Exemplified

see also p. 14

- given a LIFO list (i.e., stack) of following structure: $head \Rightarrow A \Rightarrow B \Rightarrow C$
  - with *head* stored at location L_i shared by processes P_1 and P_2
  - *push* (cf. [16, p. 11]) and *pull* adding or removing, resp., list items:

```
chain_t *cas_pull(stack_t *this) {
    chain_t *node;
    do if ((node = this->head.link) == 0) break;
    while (!CAS(&this->head.link, node, node->link));
    return node;
}
```

ABA Exemplified

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- given a LIFO list (i.e., stack) of following structure: *head* ➪ *A* ➪ *B* ➪ *C*
  - with *head* stored at location L_i shared by processes P_1 and P_2
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1 chain_t *cas_pull(stack_t *this) {
2     chain_t *node;
3     do if ((node = this->head.link) == 0) break;
4     while (!CAS(&this->head.link, node, node->link));
5     return node;
6 }
```

- assuming that the following sequence of actions will take place:

P_1
- reads head item *A* followed by *B* on the list, gets delayed at line 4
- remembers *node* = *A*, but has not yet done CAS: *head* ➪ *A* ➪ *B* ➪ *C*

P_2
- pulls head item *A* from the list: *head* ➪ *B* ➪ *C*
- pulls head item *B* from the list: *head* ➪ *C*
- pushes item *A* back to the list, now followed by *C*: *head* ➪ *A* ➪ *C*

P_1
- resumes, CAS realises *head* = *A* (followed by *B*): *head* ➪ *B* ➪ ☹
- list state *head* ➪ *A* ➪ *C* as left behind by P_2 is lost...

ABA Design Risc Reduction

- prevalent approach is to add a **change number** to the "control word" [8, p. 125], i.e., to practice some kind of **versioning**
  - this number increments at each CAS attempt on the control word
- appropriate techniques depend on the change-number parameters

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a. the values margin has a whole word size available
   - both the control and change-number word must be updated, indivisibly
   - *compare double and swap* (CDS, [8, p. 124]) of two consecutive words[9]
   - *double compare and swap* (DCAS, also CAS2 [14, p. 4-66]) of any two words

[9] See also cmpxchg8b or cmpxchg16b, in case of x86.

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b. the values margin utilizes fully unused bits in the control word itself
   - CAS facilitates indivisible updates of control word including change number
   - workaround, especially suitable for handling aligned data-structure **pointers**
   - gimmick is in data-structure padding for an object size of a power of two

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↪ an object size of 2^n bytes then gives $n - 1$ low-order bits always 0

↪ these $n - 1$ low-order bits then will be used as a **change-number tag**

↪ for **pointer operations**, the change-number tag is temporary neutralised

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↪ these $n-1$ low-order bits then will be used as a **change-number tag**
↪ for **pointer operations**, the change-number tag is temporary neutralised

- but the ABA problem never disappears, it only gets more improbable

[9] See also `cmpxchg8b` or `cmpxchg16b`, in case of x86.

Linguistic Devices for LL/SC

- as GCC does not provide atomic built-in functions for this case:

```
INLINE
long LL(long *ref) {
  long aux;

  asm volatile(
    "lwarx %0, 0, %1"
    : "=r" (aux)
    : "r" (ref));

  return aux;
}
```

```
INLINE
int SC(long *ref, long val) {
  long ccr;

  asm volatile(
    "stwcx. %2, 0, %1\n\t"
    "mfcr %0"
    : "=r" (ccr)
    : "r" (ref), "r" (val)
    : "cc", "memory");

  return ccr & 0x2;
}
```

- with "**`#define`** `INLINE` **`extern`** `inline`" for GCC to ensure that stand-alone object code is never emitted for in-line functions[10]

[10] Use "**`#define`** `INLINE inline`" for C99, for the same reason.

FAA Exemplified

- `#define FAA __sync_fetch_and_add`

```
int faa(int *p, int v) {
    return FAA(p, v);
}
```

```
faa:
        movl   4(%esp), %ecx
        movl   8(%esp), %eax
        lock
        xaddl  %eax, (%ecx)
        ret
```

FAA Exemplified

- `#define FAA __sync_fetch_and_add`

```c
int faa(int *p, int v) {
    return FAA(p, v);
}
```

```asm
faa:
        movl   4(%esp), %ecx
        movl   8(%esp), %eax
        lock
        xaddl  %eax, (%ecx)
        ret
```

- `#define AAF __sync_add_and_fetch`

```c
int aaf(int *p, int v) {
    return AAF(p, v);
}
```

```asm
aaf:
        movl   4(%esp), %ecx
        movl   8(%esp), %edx
        movl   %edx, %eax
        lock
        xaddl  %eax, (%ecx)
        addl   %edx, %eax
        ret
```

Noninvertible Operation

- safe-load of global variable G and conditional-store of $max(G, L)$ at G

```
word fax(word *ref, word val) {
  word aux;
  atomic { if ((aux = *ref) < val) *ref = val; }
  return aux;
}
```

Noninvertible Operation

fetch-and-Φ, with $\Phi = max$

- safe-load of global variable G and conditional-store of $max(G, L)$ at G

```
word fax(word *ref, word val) {
  word aux;
  atomic { if ((aux = *ref) < val) *ref = val; }
  return aux;
}
```

- conditional-store of $max(G, L)$ at G and return of $max(G, L)$

```
word xaf(word *ref, word val) {
  atomic { word aux = (*ref > val) ? *ref : *ref = val; }
  return aux;
}
```

Noninvertible Operation

- safe-load of global variable G and conditional-store of $max(G, L)$ at G

```
word fax(word *ref, word val) {
  word aux;
  atomic { if ((aux = *ref) < val) *ref = val; }
  return aux;
}
```

- conditional-store of $max(G, L)$ at G and return of $max(G, L)$

```
word xaf(word *ref, word val) {
  atomic { word aux = (*ref > val) ? *ref : *ref = val; }
  return aux;
}
```

- assuming that $G = 42$ and $L = 4711$:
  - $XAF(G, L) \equiv max(FAX(G, L), L)$: both terms result in 4711
  - $FAX(G, L) \not\equiv max(XAF(G, L), L)$: FAX may result in $42 < 4711$