

Concurrent Systems

Nebenläufige Systeme

V. Elementary Operations

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Outline

Preface

Primitive Instructions
Atomic Operations
Equivalence

Memory Models
Properties

Summary



Agenda

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Summary



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
- impartation of knowledge on memory models that are relevant to multi-threading on multi-/many-core (multi-) processors
 - 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**
- excursion into practice of **hardware features** that are of importance for the implementation of any synchronisation algorithm



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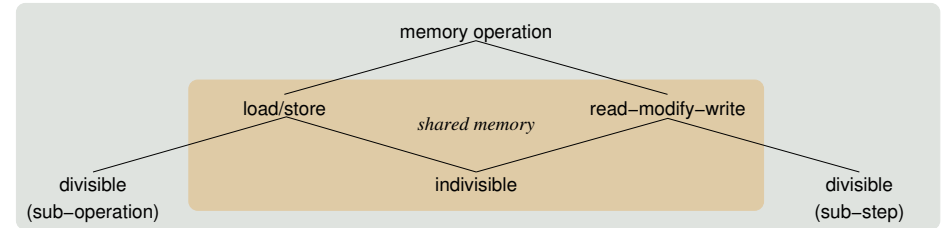
Memory Models

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Memory-Operation Semantics



- of particular interest (at this point) are **shared-memory operations**
 - commonality is the opportunity, at least, for **in 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**

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



Load/Store I

C—Level 5

```
1 #include <stdint.h>
2
3 static int64_t label;
4
5 int64_t get_label() {
6     return label;
7 }
8
9 void set_label(int64_t value) {
10    label = value;
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”**
- in physical respect these statements are **conditionally atomic**, only
 - a matter of optimisation options, the CPU, and alignment restrictions



Load/Store II

ASM—Level 4

<pre>gcc -m32... 1 get_label: 2 movl label, %eax 3 movl label+4, %edx 4 ret 5 6 set_label: 7 movl 4(%esp), %eax 8 movl 8(%esp), %ecx 9 movl %ecx, label+4 10 movl %eax, label 11 ret</pre>	<pre>gcc -m64... 12 get_label: 13 movq label(%rip), %rax 14 ret 15 16 set_label: 17 movq %rdi, label(%rip) 18 ret</pre>
--	---

- actions 2-3 and 9-10 are divisible
 - any of these 8 mov instructions is **conditionally indivisible**
- 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**



- **execution cycle** of a machine instruction that involves the ALU²
 - consists of the following individual operation steps:
 - i load input operands (acc. operation code or addressing mode, resp.)
 - ii compute result (acc. operation code)
 - iii store output operand (acc. operation code or addressing mode, resp.)
 - steps (i) and (iii) require the **bus** in case of memory-sensitive operations
 - reusable hardware resource, shareable, allocated per (load/store) step
 - typical **compound action** at instruction set architecture (ISA) level
 - is memory-sensitive only for a *complex instruction set computer* (CISC)
- in a **multiprocessor case**, the whole cycle is divisible (non-atomic)
 - merely the individual sub-steps may form indivisible actions (cf. p. 8)
 - 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

²arithmetic-logic unit, the operation unit of the CPU.

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]

- 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*
 - in terms of **main memory significance**, this translates into the following:


```
1 bool tas(byte *ref) {
2     atomic { bool aux = *ref & 0x1; *ref = 0x11111111; }
3     return aux;
4 }
```

 - with first and second operand being used to form effective address *ref*
- note that TS interlocks against simultaneous main memory accesses

³A similar effect has `ldstwb` of SPARC V9.

Test & Set II

- the original copy (IBM System/370) has **swapping characteristic**
 - *swap(x, y)*, with $x = *ref_{[0]}$ and $y = 1111111_{2[0]}$
 - for a contemporary processor (x86), this translates into the following:


```
1 int tas(any_t *ref) {      4 tas:
2     return TAS(ref);      5     movl 4(%esp), %ecx
3 }                          6     movl $1, %eax
                              7     xchgl %eax, (%ecx)
                              8     ret
```
 - whereby (using GCC atomic built-in functions):


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

 - 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)

⁴Same holds for TAS of the M68000 family and `ldstwb` of the SPARC family.

Test & Set III

Definition (Dual-Ported RAM)

A kind of random access memory (RAM) that supports simultaneous load and store operations from two directions.

- the **interlock** is conducted by a “DPRAM monitor” that, e.g. [18]:
 - 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:
 - i sets the memory location to the value given by the owning processor *and*
 - ii releases access to that memory location
- this scheme translates into a **conditional store** as follows:


```
1 word tas(word *ref) {
2     word aux;
3     atomic { if ((aux = *ref) == 0) *ref = 1; }
4     return aux;
5 }
```

Definition (CS, acc. IBM System/370)

The first and second operands are compared. If they are equal, the third operand is stored in the second-operand location. If they are unequal, the second operand is loaded into the first-operand location. [8, p. 123]

- the operation effectly performs a **conditional store** in main memory
 - The first and third operands [each are] occupying a general register. The second operand is a word in main storage. [8, p. 123]
 - in terms of **main memory significance**, this translates into the following:


```
1 atomic word cas(register old, word *ref, register new) {
2     word aux;
3     return aux = (*ref == old) ? (*ref = new) : (old = *ref);
4 }
```

 - with the actual parameters *old* and *new* being kept in general registers
- note that CS interlocks against simultaneous main memory accesses



Load-Linked/Store-Conditional I

Definition

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

- originated in the MIPS II or R6000, resp., RISC architecture [9]:
 - LL**
 - loads a word from the specified effective memory address
 - makes a **reservation** on that very address (range)⁵
 - SC**
 - checks for a reservation on the specified effective memory address⁵
 - if the reservation persists, stores the specified word at that address
 - delivers the result of the reservation check
- reasons for **cancellation** of a persisting address (range) reservation:
 - successful execution of SC—hoped for, normally
 - execution of LL by another processor applying the same address (range)
 - an exception (trap/interrupt) on the processor holding the reservation
- LL and SC interlock against simultaneous main memory accesses

⁵The dimension of the reservation depends on the hardware implementation. It may be exact the effective address or a larger address range around.



Definition (ABA, also A-B-A)

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

- when the successful execution of a CAS instruction indicates:
 - that the two operands subject to comparison are equal and, thus, purport the presence of a certain condition (*positive*),
 - but the condition is not in fact present (*false*)
- assuming that processes P_1 and P_2 simultaneously access location L_i
 - 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 $S_2 \neq S_1$
 - P_1 resumes, observes that the value of L_i equals A and, thus, acts on the assumption that the global state must be S_1 —which is no longer true
- severity of false positive execution depends on the problem (cf. p. 36)



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


```
1 int tas(long *ref) {
2     return (LL(ref) == 0) && SC(ref, 1);
3 }
```
 - in case of CAS, a memory word is conditionally overwritten ?!

```
4 int cas(long *ref, long old, long new) {
5     return (LL(ref) == old) && SC(ref, new);
6 }
```
- 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...



Definition (acc. [6, p. 17])

A value-returning instruction that operates on a global (i.e., shared) variable G and a local variable L .

- an atomic RMW instruction, inspired by “Replace Add” [3, p. 6]
 - prefix (FAA) or postfix (AAF) form, as to when fetch becomes effective
 - prefix – save the old value of G for return, then add L to G
 - postfix – add L to G , then return the new value of G
 - whereby (cf. p. 39):

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

- 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 $XAF(G, L) \equiv \max(\text{FAX}(G, L), L)$ (cf. p. 40)



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- 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]

- n processes need to interact to achieve agreement on a single data value
- note that only 1-process consensus requires no interaction
- consensus numbers of the elementary operations considered:
 - ∞ compare-and-swap, load-linked/store-conditional
 - 2 test-and-set, swap, fetch-and-add
 - 1 atomic read, atomic write
- 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



Properties Relevant to Multi-Threading

- fundamental characteristics that are of particular importance for the implementation of any synchronisation algorithm:
 - atomicity**
 - as to *how* certain machine instructions are executed
 - differentiates in RISC and CISC machines
 - specific to each ELOP that was discussed before (pp. 7–17)
 - visibility**
 - as to *when* memory-cell changes are observable
 - concerns delays in sensing the most recent memory-word write
 - introduces time factors on the availability of written data
 - ordering**
 - as to *how* memory operations appear to be performed
 - stands for a variant of *out-of-order* execution
 - reflects on (sequential, relaxed, or weak) consistency models
- these properties are linked with each other, are mutual prerequisites
 - atomicity applies to all other—and to a single machine instruction, only
 - visibility depends on the memory architecture, may cause “jitter”
 - ordering comprises multiple machine instructions, may cause “fencing”
- 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)



- 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.
 - “double” means “physically consecutive” or “logically interrelated”
 - 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)

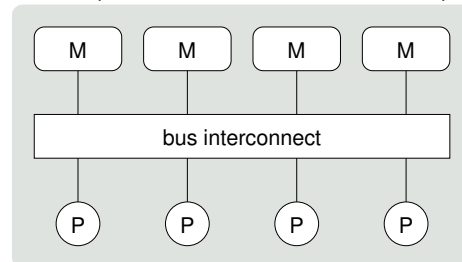
When other interacting processes will notice the changes made by the current process, and whether they will notice them at all.

- depends on the **memory architecture** and behaviour of read or write operations to the same memory location
 - UMA**
 - *uniform memory architecture* \leadsto the same access time
 - each address is assigned a fixed home in the global address space
 - NUMA**
 - *non-uniform memory architecture* \leadsto different access times
 - each address is assigned a fixed home in the global address space
 - each processor (“NUMA node”) uses private (local) memory, too
 - COMA**
 - *cache-only memory architecture* \leadsto different access times
 - no address is assigned a fixed home in the global address space
 - each processor uses private (local) memory, only
- 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

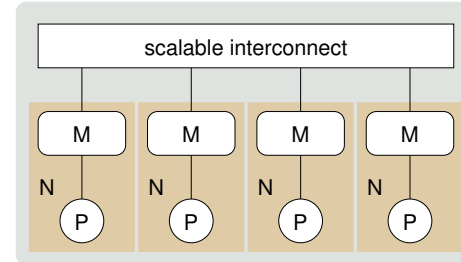
Memory Architectures at a Glance

Simplified

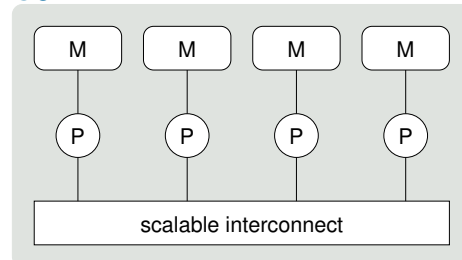
UMA (*symmetric multiprocessing, SMP*)



NUMA



COMA



- NUMA node (N)
 - zone of uniform memory characteristic
- NUMA/COMA distance
 - number of (network) hops to distant memory
- UMA/NUMA combination

Ordering

What memory re-orderings are possible for a process, relatively to the order as specified by its program.

- to improve performance, memory-sensitive machine instructions are not executed in the order originally specified by the program
 - on the one hand, the compiler reorders ($L3$) instructions⁶ before run-time
 - on the other hand, the CPU reorders ($L2$) instructions⁶ at run-time
 - it is this aspect of **dynamic ordering** that is of relevance in the following
- mainly, dynamic ordering is an issue of non-blocking synchronisation
 - as blocking synchronisation implicitly can take care of “fencing” proper
 - depending on the kind of critical section and type of data dependency
 - but, critical section *per se* is no guarantee for memory ordering (cf. p. 25)
- ordering ensuring needs special instructions: **memory barrier/fence**

⁶According to the actual level of abstraction: operating-system machine ($L3$) or instruction set architecture ($L2$) level. See also [10] or [17, p. 34].

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

```

1 int a = 1, b = 2;
2
3 void ab_set() {
4     a = 3;
5     b = 4;
6 }
    
```

- what values of *a* and *b* do other processors see once line 6 has been reached by one processor?
 - (1, 2), (1, 4), (3, 2), (3, 4)
 - depending on processor and memory architecture
- writes are not necessarily seen by other processors in the order as specified by the program!

- assuming that the next function is executed directly afterwards to the former one just discussed, but by a different processor:

```

7 void ab_get(int ab[2]) {
8     ab[0] = b;
9     ab[1] = a;
10 }
    
```

- 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*



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]

- ld_a LoadLoad ld_b
 - ensures that *a* is read before *b* is accessed⁷
 - speculative loads, out-of-order processing
- st_a StoreStore st_b
 - ensures that *a* is visible before *b* is flushed⁷
 - disordered flushes from write buffers
- ld_a LoadStore st_b
 - ensures that *a* is read before *b* is flushed⁷
 - out-of-order processors that can bypass loads
- st_a StoreLoad ld_b
 - ensures that *a* is visible before *b* is accessed⁷
 - write to *same* location by another processor
- 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

⁷Including the execution of all subsequent loads or stores, resp.



- 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]
- relaxed**
 - in terms of the constraints defined by sequential consistency
 - as to (i) program order, (ii) write atomicity, or (iii) both:
 - write to read, write to write, read to read and read to write
 - read other’s, write early
 - read own, write early
 - pertaining to (i) different or (ii) same memory locations
- weak**
 - “limited to hardware-recognized synchronizing variables” [4]
 - yet weaker tendencies: release [5] and entry [1] consistency
 - implemented by operating system machine level programs
 - usually not provided by the instruction set architecture level

- state of the art processors provide relaxed or weak consistency models

⁸Weaker than “strict consistency” that requires a read from a memory location to return the value of the most recent write.



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- 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
 - sequential, relaxed, and weak **data consistency**
- **hardware features** that are of importance for the implementation of any synchronisation algorithm
 - including but not limited to non-blocking synchronisation, especially



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Unconditional Store: Workaround

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

```

1 word tas(word *ref) {
2     atomic { word aux = *ref; *ref = 1; }
3     return aux;
4 }
```

- same is true when using the GCC atomic built-in function (x86, cf. p11):

```

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

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

```

6 int tas(long *ref) {
7     return CAS(ref, 0, 1);
8 }
9 tas:
10 xorl    %eax, %eax
11 movl   $1, %ecx
12 movl   4(%esp), %edx
13 lock
14 cpxchgl %ecx, (%edx)
15 testl  %eax, %eax
16 sete  %al
17 movzbl %al, %eax
18 ret
```

- worst-case overhead of five instructions (cf. p11)
- pays off, depending on processor and cache architecture



ABA Exemplified

see also p. 14

- given a LIFO list (i.e., stack) of following structure: $head \leftrightarrow A \leftrightarrow B \leftrightarrow C$
 - 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:

```

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: $head \leftrightarrow A \leftrightarrow B \leftrightarrow C$
 - P_2 pulls head item A from the list: $head \leftrightarrow B \leftrightarrow C$
 - pulls head item B from the list: $head \leftrightarrow C$
 - pushes item A back to the list, now followed by C : $head \leftrightarrow A \leftrightarrow C$
 - P_1 resumes, CAS realises $head = A$ (followed by B): $head \leftrightarrow B \leftrightarrow \odot$
 - list state $head \leftrightarrow A \leftrightarrow C$ as left behind by P_2 is lost...



- 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
 - 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 words⁹
 - double compare and swap* (DCAS, also CAS2 [14, p. 4-66]) of any two words
 - 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
 - ↔ 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
- but the ABA problem never disappears, it only gets more improbable

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

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

```

1 long LL(long *ref) {
2     long aux;
3
4     asm volatile(
5         "lwarx %0, 0, %1"
6         : "=r" (aux)
7         : "r" (ref));
8
9     return aux;
10 }
11 inline int SC(long *ref, long val) {
12     long ccr;
13
14     asm volatile(
15         "stwcx. %2, 0, %1\n\t"
16         "mfcr %0"
17         : "=r" (ccr)
18         : "r" (ref), "r" (val)
19         : "cc", "memory");
20
21     return ccr & 0x2;
22 }

```

- with “`#define INLINE extern inline`” for GCC to ensure that stand-alone object code is never emitted for in-line functions¹⁰

¹⁰Use “`#define INLINE inline`” for C99, for the same reason.

FAA Exemplified

GCC Atomic Built-in Functions, x86

- `#define FAA __sync_fetch_and_add`

```

1 int faa(int *p, int v) {
2     return FAA(p, v);
3 }
4 faa:
5     movl 4(%esp), %ecx
6     movl 8(%esp), %eax
7     lock
8     xaddl %eax, (%ecx)
9     ret

```

- `#define AAF __sync_add_and_fetch`

```

10 int aaf(int *p, int v) {
11     return AAF(p, v);
12 }
13 aaf:
14     movl 4(%esp), %ecx
15     movl 8(%esp), %edx
16     movl %edx, %eax
17     lock
18     xaddl %eax, (%ecx)
19     addl %edx, %eax
20     ret

```

Noninvertible Operation

fetch-and-Φ, with $\Phi = \max$

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

```

1 word fax(word *ref, word val) {
2     word aux;
3     atomic { if ((aux = *ref) < val) *ref = val; }
4     return aux;
5 }

```

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

```

6 word xaf(word *ref, word val) {
7     atomic { word aux = (*ref > val) ? *ref : *ref = val; }
8     return aux;
9 }

```

- 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 $42 < 4711$