Concurrent Systems

Nebenläufige Systeme

V. Elementary Operations

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Agenda

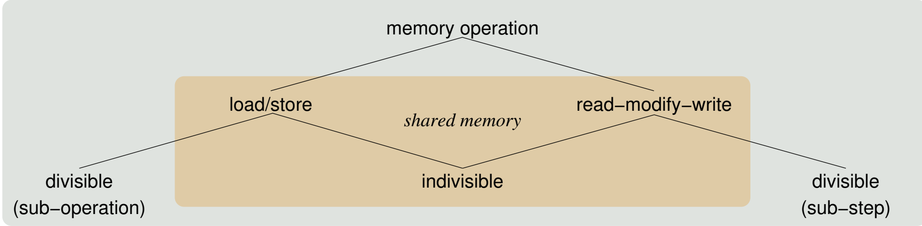
Outline

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
- 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

Outline

Memory-Operation Semantics



- 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—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

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
```

gcc -m64...

```
12 get_label:
13   movq label(%rip), %rax
14   ret
15
16 set_label:
17   movq %rdi, label(%rip)
18   ret
```

- 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***

Read-Modify-Write

- **execution cycle** of a machine instruction that involves the ALU[2]
  - 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

[2] *arithmetic-logic unit*, the operation unit of the CPU.

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]

- 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:

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

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

[3] A similar effect has `ldstub` of SPARC V9.

Test & Set II

- the original copy (IBM System/370) has **swapping characteristic**
  - *swap*(x, y), with $x = *ref_{[0]}$ and $y = 11111111_{2[0]}$
  - for a contemporary processor (x86), this translates into the following:

```
int tas(any_t *ref) {
    return TAS(ref);
}
```

```
tas:
    movl   4(%esp), %ecx
    movl   $1, %eax
    xchgl  %eax, (%ecx)
    ret
```

  - whereby (using GCC atomic built-in functions):

```
#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)

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

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

Compare & Swap I

CAS

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:

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

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

Compare & Swap II

Ambiguity (cf. also [8, p. 125])

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:
  - 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*)
- 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 I

LL/SC

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 address[5]
    - 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:
  - i successful execution of SC—hoped for, normally
  - ii execution of LL by another processor applying the same address (range)
  - iii an exception (trap/interrupt) on the processor holding the reservation
- LL and SC interlock against simultaneous main memory accesses

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

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

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

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

```
int cas(long *ref, long old, long new) {
    return (LL(ref) == old) && SC(ref, new);
}
```

- 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...

Fetch & Add

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):

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

- 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]

- 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

Outline

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)

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.
      - "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)

Visibility

Hegemony of ccNUMA—still

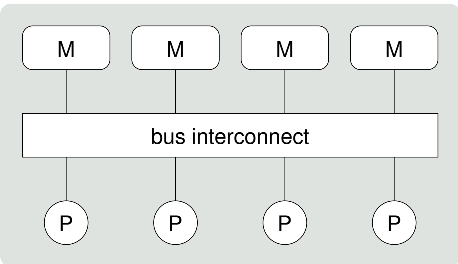
When other interacting processes will notice the changes made by the current process, and whether they will notice them at all.

- depends on the **memory architecture** and behaviour of read or write operations to the same memory location
  - UMA
    - *uniform memory architecture* ⇝ the same access time
    - each address is assigned a fixed home in the global address space
    - no processor uses private (local) memory besides shared memory
  - NUMA
    - *non-uniform memory architecture* ⇝ 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* ⇝ 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

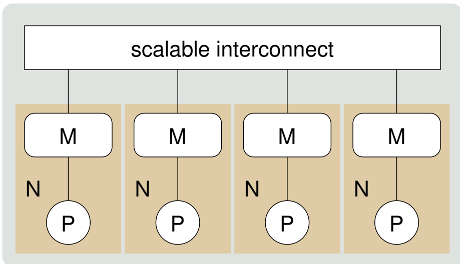
Memory Architectures at a Glance

Simplified

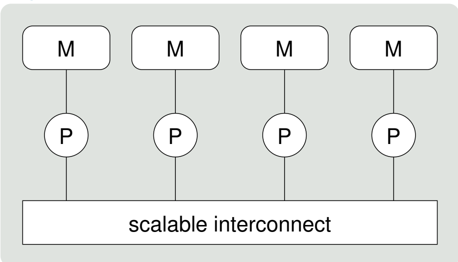
UMA (*symmetric multiprocessing*, SMP)



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 (*L*3) instructions[6] before run-time
  - on the other hand, the CPU reorders (*L*2) instructions[6] 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**

[6] According to the actual level of abstraction: operating-system machine (*L*3) or instruction set architecture (*L*2) level. See also [10] or [17, p. 34].

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:

```
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 Barriers

> *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 accessed[7]
  - speculative loads, out-of-order processing
- st_a StoreStore st_b
  - ensures that *a* is visible before *b* is flushed[7]
  - disordered flushes from write buffers
- ld_a LoadStore st_b
  - ensures that *a* is read before *b* is flushed[7]
  - out-of-order processors that can bypass loads
- st_a StoreLoad ld_b
  - ensures that *a* is visible before *b* is accessed[7]
  - 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

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

Consistency Models

- **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:
  - i write to read, write to write, read to read and read to write
  - ii read other's, write early
  - iii 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

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

Outline

Preface

Primitive Instructions
- Atomic Operations
- Equivalence

Memory Models
- Properties

Summary

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
  - 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:

```
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)
```

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

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

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

  - worst-case overhead of five instructions (cf. p 11)
  - 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* ➪ *A* ➪ *B* ➪ *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* ➪ *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

  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

  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

    ↪ 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

[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
```

- **#define** AAF `__sync_add_and_fetch`

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

```
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;
}
```

- 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 $42 < 4711$