What I learned from Mike

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What I learned from Mike

or

How I Got my Start in Nonperturbative QCD

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A Story Unknown

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How I Got my Start in Nonperturbative QCD

A Story Unknown

(even to Mike)

QCD in the late ’70s

- QCD was invented in 1973, and lattice QCD almost immediately thereafter.
  - In the late 70s, Wilson was working on relatively formal topics, implementing chiral symmetry in lattice QCD.
  - Others were attempting hadron calculations with strong coupling calculations of uncertain reliability.

- As a graduate student at Cornell then, lattice QCD made an enormous impression on me as a way to understand what renormalization, anomalous dimensions, and beta functions were,
  - not as a way of actually calculating things.
  - I did as my thesis a difficult perturbative QCD calculation.

- The practical achievements of QCD in the ‘70s were short distance calculations done with perturbation theory.
  - QED experts found that the methods in which they were expert could be applied to very interesting QCD problems as well.
- In PQCD circles at the time, one often heard statements like, “The moments of structure functions are nonperturbative and incalculable, but the q^2 evolution of the moments can be calculated with QCD”.
- At Cornell we were taught that this was pernicious nonsense.
  - There was one QCD. DimReg perturbation theory approximated it well at short distances; lattice QCD would eventually solve it everywhere.
  - But for the time being, little could be calculated.

The ’79-’80 revolution

- In 1981 when I finished my thesis, I found that a revolution had occurred:
  - M. Creutz had introduced Monte Carlo methods to lattice QCD and had shown how to calculate a physical quantity, the string tension.
  - Others had shown how Monte Carlo methods could be used to calculate the hadron spectrum.
- Someone gave me a copy of one of Creutz’s programs, and as a postdoc at Fermilab I began to study it.
  - The program made an huge impression on me, and I began to consider it something very beautiful.

What was this earth-shaking program?

What was this earth-shaking program?

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     000150
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
* LATTICE=ISIZE*ISIZE*ISIZE*ISIZE                                       000220
* INVERSE TEMPERATURE = B                                              000230
* SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK           000240
*MUP AND MDOWN ARE DIMENSIONED TO ISIZE                                 000270
*DO NOT RUN WITH B=0                                                   000280
      ISIZE=10                                                          000290
      B=2.6                                                             000300
      NMAX=ISIZE                                                        000310
      DO5N=1,NMAX                                                       000320
      MUP(N)=MOD(N,ISIZE)+1                                             000330
5     MDOWN(N)=MOD(N-2+ISIZE,ISIZE)+1                                   000340
      DO6N=1,5                                                          000350
6     IPOWER(N)=ISIZE**(N-1)                                            000360
      MF=4*ISIZE**4                                                     000370
      DO67M=1,MF                                                        000380
      ALAT1(M)=1                                                        000390
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
                                                                        000580
      SUBROUTINE MONTE(ITER)                                            000590
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000600
      COMMON/VAR1/ALAT1(40000)                                          000610
      COMMON/VAR2/ALAT2(40000)                                          000620
      LEVEL2,ALAT1,ALAT2                                                000630
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000640
      COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1         000650
      COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2         000660
      INTEGER X(4)                                                      000670
      PRINT*,ITER,"ITERATION(S)"                                        000680
      TEMP=1/B                                                          000690
      DO51NIT=1,ITER                                                    000700
      SUM=0                                                             000710
*SITE LOOPS                                                            000720
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000730
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000750
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000760
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000770
*SELECT LINK                                                           000780
      DO 50 I1=1,4                                                      000790
      UINT1=UINT2=0                                                     000800
*LOCATE NEXT SITE IN I1 DIRECTION                                      000810
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))                                 000820
      M5=M1+M45                                                         000830
      I1IP5=I1*IPOWER(5)                                                000840
      L15=M1+I1IP5                                                      000850
*LOOP OVER PLANES CONTAINING LINK                                      000860
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1                                     000870
*LOCATE NEIGHBORING SITES AND LINKS                                    000880
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000900
      M4=M3+M45                                                         000910
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
      L34=M3+I1IP5                                                      000950
      L45=M4+I2IP5                                                      000960
      L56=M5+I2IP5                                                      000970
      L26=M2+I1IP5                                                      000980
*OBTAIN INTERACTING SPINS                                              000990
      A12S1=ALAT1(L12)$A12S2=ALAT2(L12)                                 001000
      A26S1=ALAT1(L26)$A26S2=ALAT2(L26)                                 001010
      A34S1=ALAT1(L34)$A34S2=ALAT2(L34)                                 001020
      A45S1=ALAT1(L45)$A45S2=ALAT2(L45)                                 001030
      A65S1=CONJG(ALAT1(L56))$A65S2=-ALAT2(L56)                         001040
      A13S1=CONJG(ALAT1(L31))$A13S2=-ALAT2(L31)                         001050
*MULTIPLY INTERACTING SPINS                                            001060
      A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)                             001070
      A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)                             001080
      A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)                             001090
      A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)                             001100
      UINT1=UINT1+A126S1*A65S1                                          001110
     C  -A126S2*CONJG(A65S2)                                            001120
     C  +A134S1*A45S1                                                   001130
     C  -A134S2*CONJG(A45S2)                                            001140
      UINT2=UINT2+A126S1*A65S2                                          001150
     C  +A126S2*CONJG(A65S1)                                            001160
     C  +A134S1*A45S2                                                   001170
     C  +A134S2*CONJG(A45S1)                                            001180
1     CONTINUE                                                         001190
*SELECT NEW GROUP ELEMENT                                              001200
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001210
      UMAGIN=1/UMAG                                                     001220
      BAG=UMAGIN*TEMP                                                   001230
      OME2B=1-EXP(-2*B*UMAG)                                            001240
6     A0=1.+ALOG(1.-OME2B*RANF(0))*BAG                                  001250
      RAD=1-A0**2                                                       001260
      IF(RANF(0)**2.GT.RAD)GOTO6                                        001270
      A3=SQRT(RAD)*(2*RANF(0)-1.)                                       001280
8     A1=RANF(0)-.5$A2=RANF(0)-.5                                       001290
      AMAG=A1**2+A2**2                                                  001300
      IF(AMAG.GT..25)GOTO8                                              001310
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001320
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001330
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001340
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001350
      SUM=SUM+A0*UMAG                                                   001360
50    CONTINUE                                                          001370
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001380
      PRINT100,ISIZE,B,APQ                                              001390
100   FORMAT("      ISIZE=",I2,"    GROUP=SU(2)",                       001400
     CONT  "     B=",F6.4,"     AV.PQ.=",F6.4)                         001410
51    CONTINUE                                                          001420
      RETURN                                                            001430
      END                                                               001440
```

What was this earth-shaking program?

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     000150
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
* LATTICE=ISIZE*ISIZE*ISIZE*ISIZE                                       000220
* INVERSE TEMPERATURE = B                                              000230
* SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK           000240
*MUP AND MDOWN ARE DIMENSIONED TO ISIZE                                 000270
*DO NOT RUN WITH B=0                                                   000280
      ISIZE=10                                                          000290
      B=2.6                                                             000300
      NMAX=ISIZE                                                        000310
      DO5N=1,NMAX                                                       000320
      MUP(N)=MOD(N,ISIZE)+1                                             000330
5     MDOWN(N)=MOD(N-2+ISIZE,ISIZE)+1                                   000340
      DO6N=1,5                                                          000350
6     IPOWER(N)=ISIZE**(N-1)                                            000360
      MF=4*ISIZE**4                                                     000370
      DO67M=1,MF                                                        000380
      ALAT1(M)=1                                                        000390
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
                                                                        000580
      SUBROUTINE MONTE(ITER)                                            000590
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000600
      COMMON/VAR1/ALAT1(40000)                                          000610
      COMMON/VAR2/ALAT2(40000)                                          000620
      LEVEL2,ALAT1,ALAT2                                                000630
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000640
      COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1         000650
      COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2         000660
      INTEGER X(4)                                                      000670
      PRINT*,ITER,"ITERATION(S)"                                        000680
      TEMP=1/B                                                          000690
      DO51NIT=1,ITER                                                    000700
      SUM=0                                                             000710
*SITE LOOPS                                                            000720
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000730
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000750
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000760
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000770
*SELECT LINK                                                           000780
      DO 50 I1=1,4                                                      000790
      UINT1=UINT2=0                                                     000800
*LOCATE NEXT SITE IN I1 DIRECTION                                      000810
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))                                 000820
      M5=M1+M45                                                         000830
      I1IP5=I1*IPOWER(5)                                                000840
      L15=M1+I1IP5                                                      000850
*LOOP OVER PLANES CONTAINING LINK                                      000860
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1                                     000870
*LOCATE NEIGHBORING SITES AND LINKS                                    000880
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000900
      M4=M3+M45                                                         000910
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
```

```
      L34=M3+I1IP5                                                      000950
      L45=M4+I2IP5                                                      000960
      L56=M5+I2IP5                                                      000970
      L26=M2+I1IP5                                                      000980
*OBTAIN INTERACTING SPINS                                              000990
      A12S1=ALAT1(L12)$A12S2=ALAT2(L12)                                 001000
      A26S1=ALAT1(L26)$A26S2=ALAT2(L26)                                 001010
      A34S1=ALAT1(L34)$A34S2=ALAT2(L34)                                 001020
      A45S1=ALAT1(L45)$A45S2=ALAT2(L45)                                 001030
      A65S1=CONJG(ALAT1(L56))$A65S2=-ALAT2(L56)                         001040
      A13S1=CONJG(ALAT1(L31))$A13S2=-ALAT2(L31)                         001050
*MULTIPLY INTERACTING SPINS                                            001060
      A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)                             001070
      A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)                             001080
      A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)                             001090
      A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)                             001100
      UINT1=UINT1+A126S1*A65S1                                          001110
     C  -A126S2*CONJG(A65S2)                                            001120
     C  +A134S1*A45S1                                                   001130
     C  -A134S2*CONJG(A45S2)                                            001140
      UINT2=UINT2+A126S1*A65S2                                          001150
     C  +A126S2*CONJG(A65S1)                                            001160
     C  +A134S1*A45S2                                                   001170
     C  +A134S2*CONJG(A45S1)                                            001180
1     CONTINUE                                                         001190
*SELECT NEW GROUP ELEMENT                                              001200
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001210
      UMAGIN=1/UMAG                                                     001220
      BAG=UMAGIN*TEMP                                                   001230
      OME2B=1-EXP(-2*B*UMAG)                                            001240
6     A0=1.+ALOG(1.-OME2B*RANF(0))*BAG                                  001250
      RAD=1-A0**2                                                       001260
      IF(RANF(0)**2.GT.RAD)GOTO6                                        001270
      A3=SQRT(RAD)*(2*RANF(0)-1.)                                       001280
8     A1=RANF(0)-.5$A2=RANF(0)-.5                                       001290
      AMAG=A1**2+A2**2                                                  001300
      IF(AMAG.GT..25)GOTO8                                              001310
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001320
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001330
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001340
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001350
      SUM=SUM+A0*UMAG                                                   001360
50    CONTINUE                                                          001370
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001380
      PRINT100,ISIZE,B,APQ                                              001390
100   FORMAT("      ISIZE=",I2,"    GROUP=SU(2)",                       001400
     CONT  "     B=",F6.4,"     AV.PQ.=",F6.4)                         001410
51    CONTINUE                                                          001420
      RETURN                                                            001430
      END                                                               001440
```

My notes from 1981.

- I found I could understand the whole program just by reading it.
  - The lattices were called U,
  - the analogs of vector potentials were called A,
  - links were L, sites were M.

```
      SUM=0
*SITE LOOPS
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)
*SELECT LINK
      DO 50 I1=1,4
      UINT1=UINT2=0
*LOCATE NEXT SITE IN I1 DIRECTION
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))
      M5=M1+M45
      I1IP5=I1*IPOWER(5)
      L15=M1+I1IP5
*LOOP OVER PLANES CONTAINING LINK
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1
*LOCATE NEIGHBORING SITES AND LINKS
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))
```

$ not allowed on IBM !

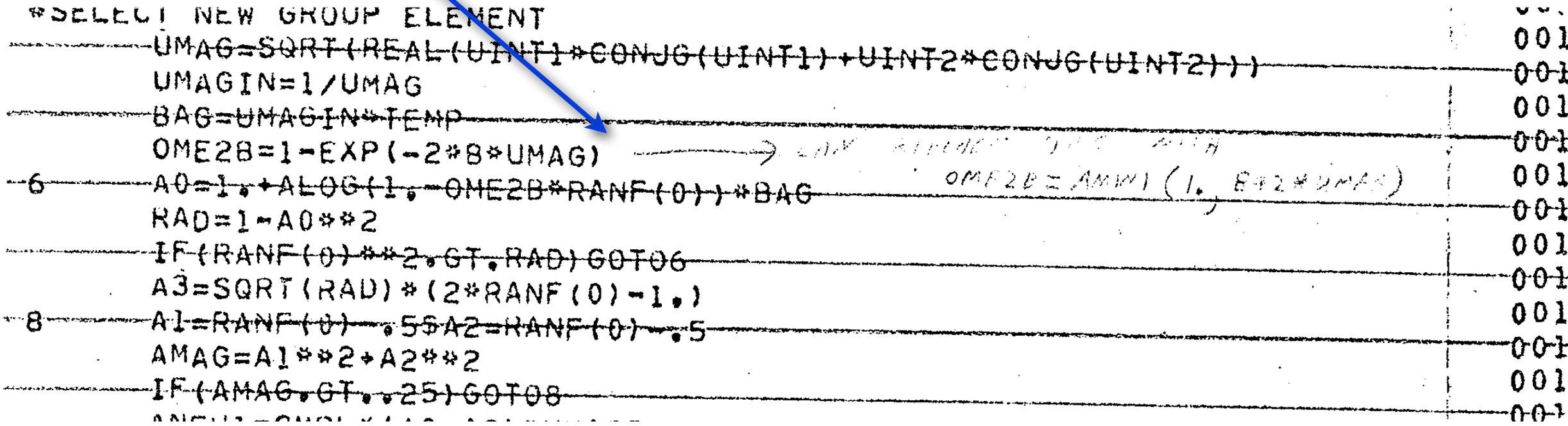
2 × × 6

L12

1 × ← L15 → × 5

3 × × 4

- I got stuck at OME2B.
  - Had to actually read the manual (the Phys Rev D article).



Science results

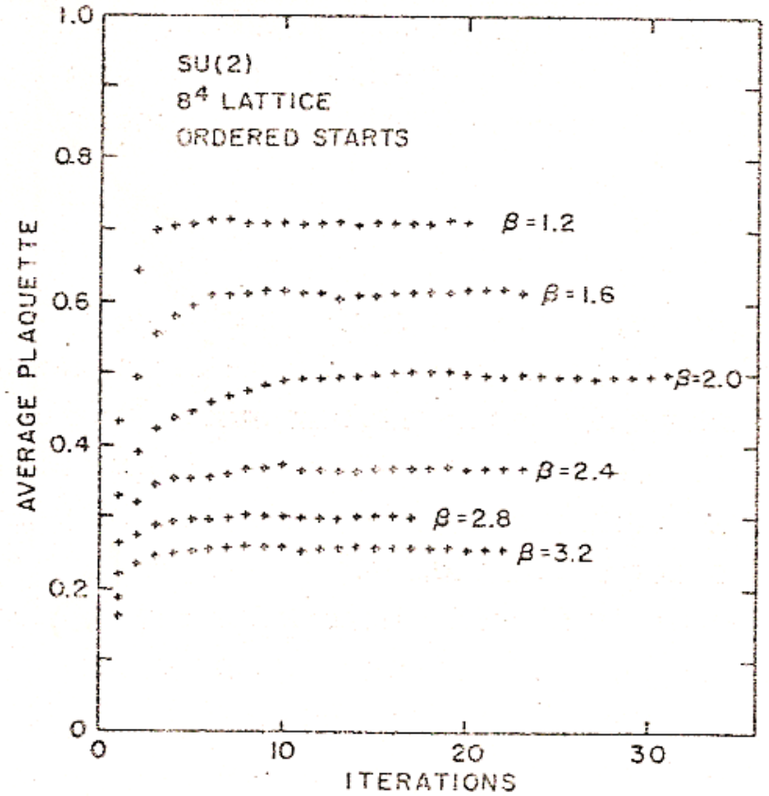


FIG. 2. The evolution of the average plaquette at several values of β.

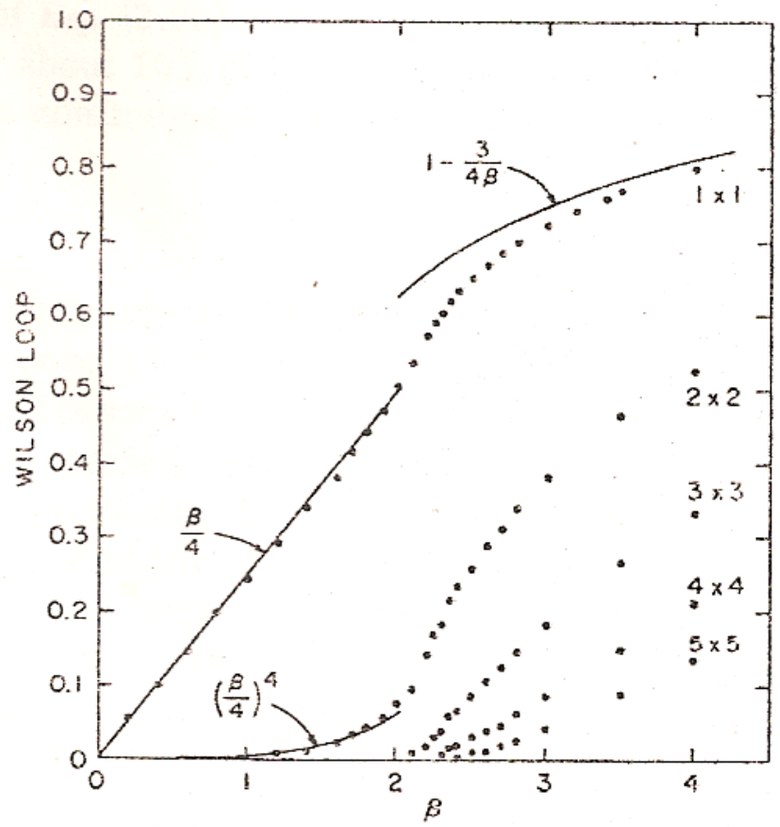


FIG. 4. Wilson loops as a function of β.

square Wilson loops at $\beta = 3$ as a function of lattice size. These loops are taken to lie in a fundamental plane of the lattice and are up to six links on a side. Each measurement is an average over all similar loops in the lattice and the error bars represent the standard deviation for the fluctua-

strong-coupling result

$$W(\square) \underset{\beta \to 0}{\sim} \tfrac{1}{4}\beta, \qquad W(2\times 2) \underset{\beta \to 0}{\sim} (\tfrac{1}{4}\beta)^4, \tag{4.1}$$

and the weak-coupling limit[10]

Science results

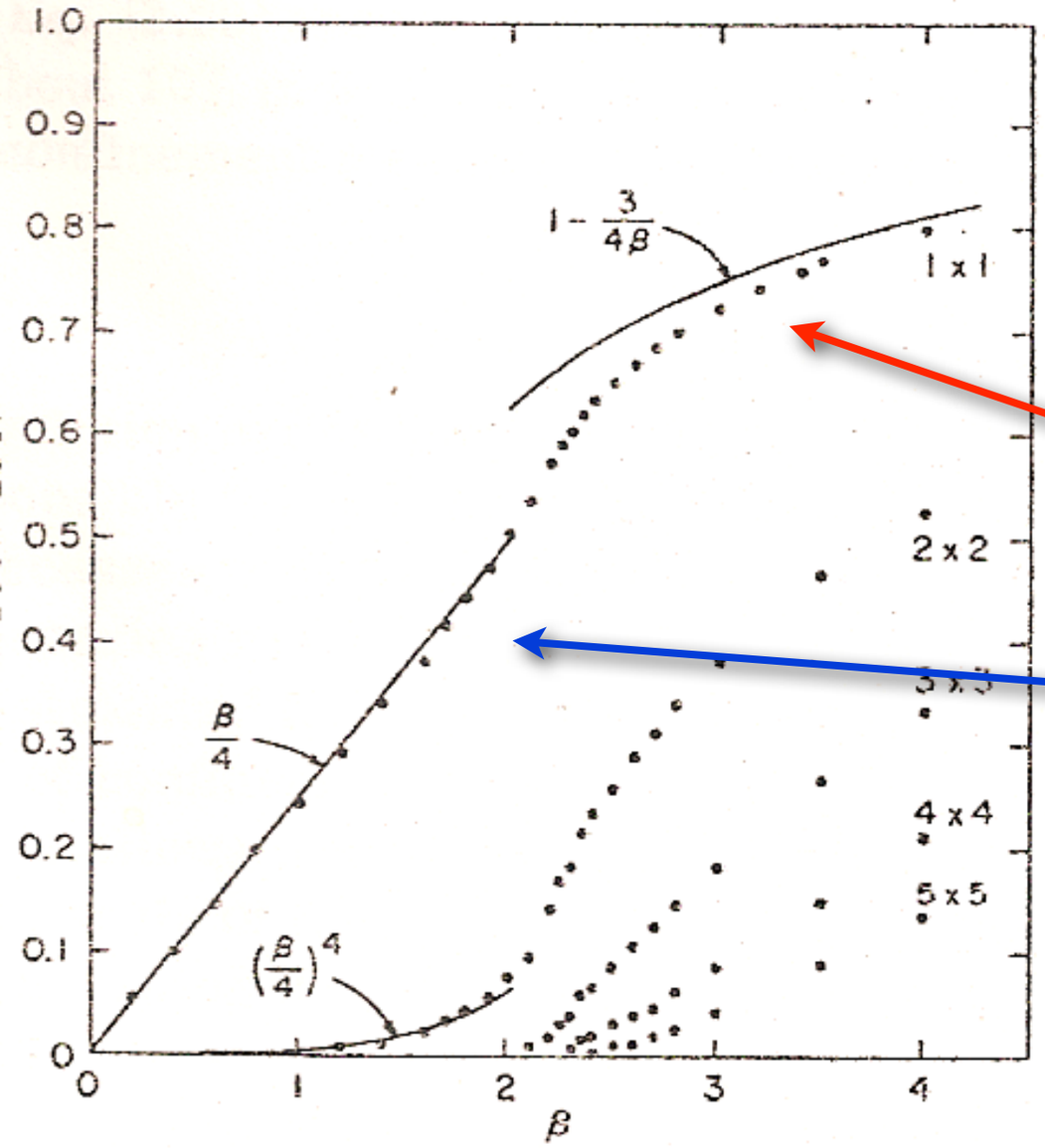


FIG. 4. Wilson loops as a function of β.

-coupling result

□) $\underset{\beta\to 0}{\sim} \frac{1}{4}\beta$,

(4.1)

The plaquette:
agrees with PT at low g^2, short distances,
nonperturbative at high g^2, long distances.

This was the real QCD that we'd been told to expect!

This was a real revolution.

Science results

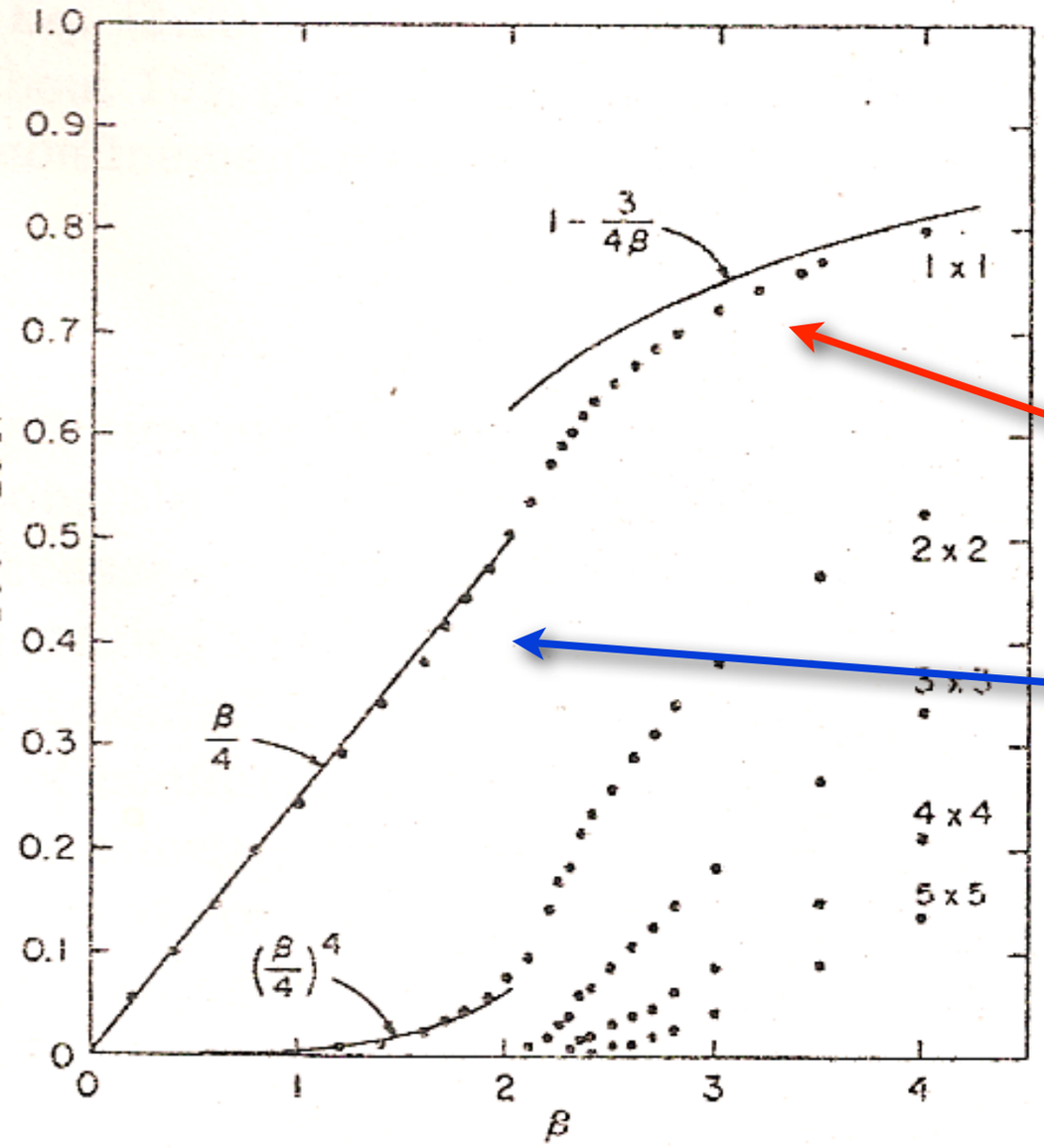


FIG. 4. Wilson loops as a function of β.

-coupling result

□) $\underset{\beta\to 0}{\sim} \frac{1}{4}\beta$,

(4.1)

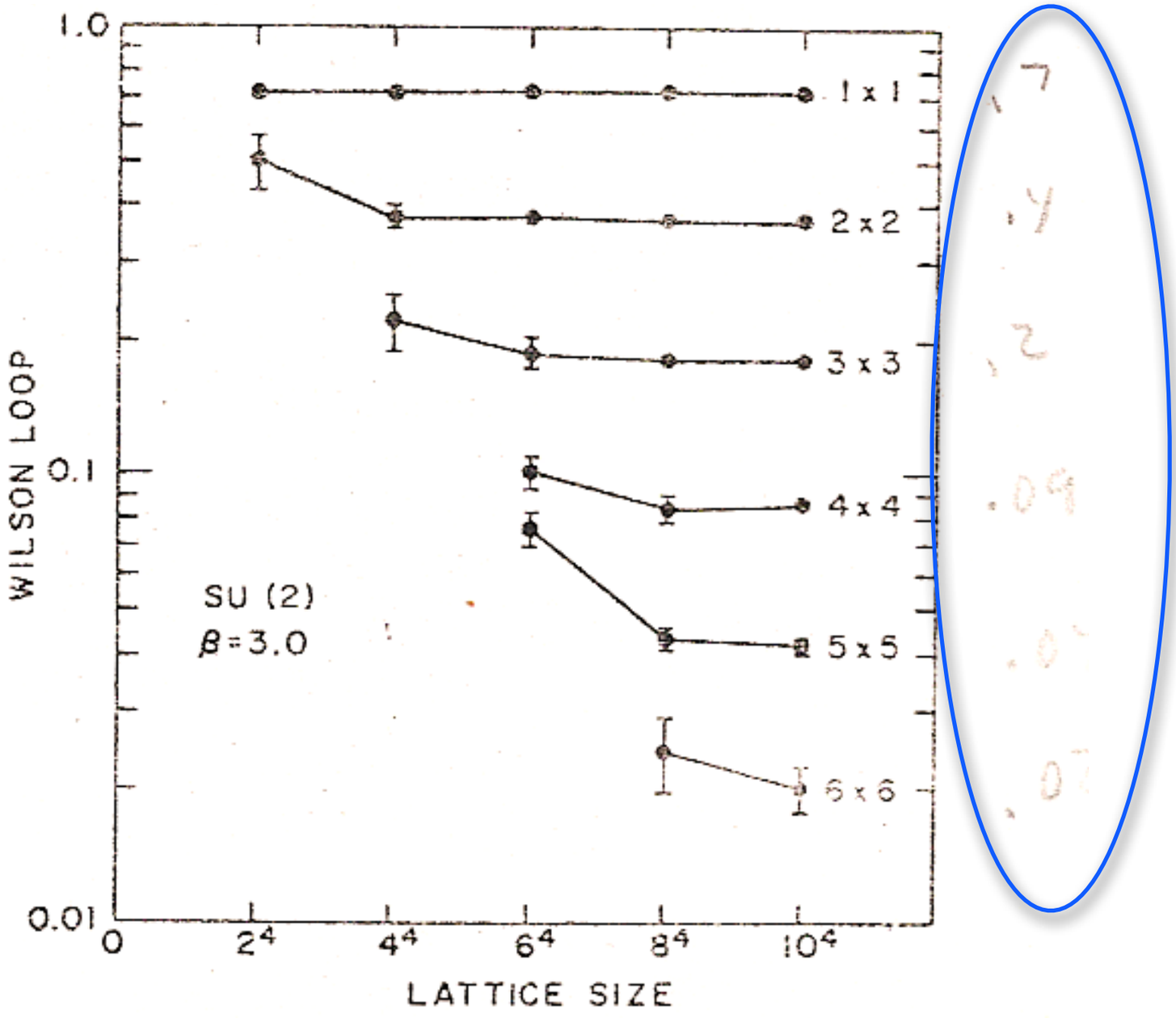
This agreement with PT later became a topic of research for me.
This was the first instance that I had seen in a real calculation.

The plaquette:
agrees with PT at low g^2, short distances,
nonperturbative at high g^2, long distances.

This was the real QCD that we'd been told to expect!

This was a real revolution.

Science results



!

FIG. 3. Wilson loops at $\beta = 3$ as a function of lattice size.

Science results: $\sqrt{(K)}/\Lambda$

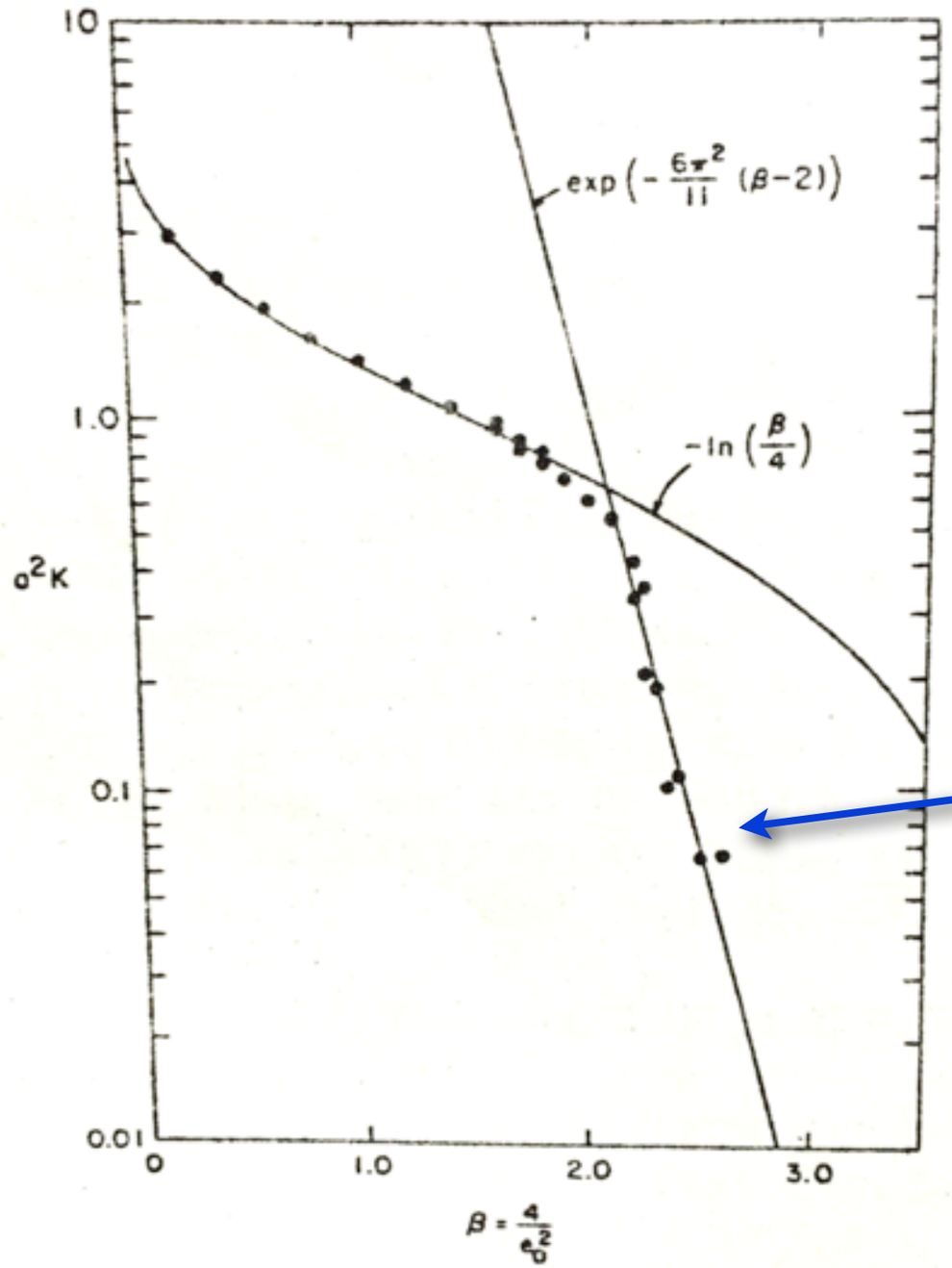


FIG. 6. The cutoff squared times the string tension as a function of β. The solid lines are the strong- and weak-coupling limits.

String tension scales as it should from perturbation theory at small lattice spacing.

```
100   *  lattice
200            common/var/b,isize,mdown(4),mup(4),ipower(5),apq
300            common/var1/alat1(1024)
400            common/var2/alat2(1024)
500            complex alat1,alat2
600   * lattice=isize**4
700   * inverse temperature=b
800   * subroutine monte(i) gives i monte carlo iterations per link
900   * mup and mdown are dimensioned to isize
1000  * do not run with b=0.
1100           isize=4
1200           b=2.0
1300           nmax=isize
1400           do 5 n=1,nmax
1500           mup(n)=mod(n,isize)+1
1700  5        mdown(n)=mod(n-2+isize,isize)+1
1800           do 6 n=1,5
1900  6        ipower(n)=isize**(n-1)
2000           mf=4*isize**4
2100           do 67 i=1,mf
2200           alat1(i)=1.
2300  67       alat2(i)=0.
2400           call monte(100)
2500           stop
2600           end
2700
2800
2900
3000           subroutine monte(iter)
3100           common/var/b,isize,mdown(4),mup(4),ipower(5),apq
3200           common/var1/alat1(1024)
3300           common/var2/alat2(1024)
3400           complex alat1,alat2
3500           complex uint1,uint2,anew1,anew2
3600           complex a12s1,a26s1,a65s1,a13s1,a34s1,a45s1,a126s1,a134s1
3700           complex a12s2,a26s2,a65s2,a13s2,a34s2,a45s2,a126s2,a134s2
3800           integer x(4)
3900           print*,iter,'iterations'
4000           temp=1./b
4050           iran=1234
4100           do 51 nit=1,iter
4200           sum=0.
4300  * select site
4400           ma=-ipower(2)-ipower(3)-ipower(4)-ipower(5)
4500           do 50 is=1,isize,2
4600           do 50 js=1,isize,2
4700           do 50 ks=1,isize,2
4800           do 50 ls=1,isize,2
4900           x(1)=is+mod(ib,2)
5000           x(2)=js+mod(ib/2,2)
5100           x(3)=ks+mod(ib/4,2)
5200           x(4)=ls+mod(ib/8,2)
5300           m1=ma+is*ipower(1)+js*ipower(2)+ks*ipower(3)+ls*ipower(4)
5400  * select link
5500           do 50 i1=1,4
5600           uint1=0.
5700           uint2=0.
5800  * locate next site in i1 direction
5900           m45=ipower(i1)*(mup(x(i1))-x(i1))
6000           m5=m1+m45
6100           i1ip5=i1*ipower(5)
```

Once I completely understood the program, I began to experiment with it.

```
*  lattice
      common/var/b,isize,mdown(4),mup(4),ipower(5),apq
      common/var1/alat1(1024)
      common/var2/alat2(1024)
      complex alat1,alat2
* lattice=isize**4
* inverse temperature=b
* subroutine monte(i) gives i monte carlo iterations per link
* mup and mdown are dimensioned to isize
* do not run with b=0.
      isize=4
      b=2.0
      nmax=isize
      do 5 n=1,nmax
      mup(n)=mod(n,isize)+1
5     mdown(n)=mod(
      do 6 n=1,5
6     ipower(n)=isi
      mf=4*isize**4
      do 67 i=1,mf
      alat1(i)=1.
67    alat2(i)=0.
      call monte(1(
      stop
      end

      subroutine m(
      common/var/b,
      common/var1/a
      common/var2/a
      complex alat
      complex uint
      complex a12s
      complex a12s
      integer x(4)
      print*,iter,
      temp=1./b
      iran=1234
      do 51 nit=1,
      sum=0.
* select site
      ma=-ipower(2)-ipower(3)-ipower(4)-ipower(5)
      do 50 is=1,isize,2
      do 50 js=1,isize,2
      do 50 ks=1,isize,2
      do 50 ls=1,isize,2
      x(1)=is
      x(2)=js
      x(3)=ks
      x(4)=ls
      m1=ma+is*ipower(1)+js*ipower(2)+ks*ipower(3)+ls*ipower(4)
* select link
      do 50 i1=1,4
      uint1=0.
      uint2=0.
* locate next site in i1 direction
      m45=ipower(i1)*(mup(x(i1))-x(i1))
      m5=m1+m45
      i1ip5=i1*ipower(5)
```

Once I completely understood the program, I began to experiment with it.

Go from 4^4 to 8^4 lattice!

```
100   *  lattice
200            common/var/b,isize,mdown(4),mup(4),ipower(5),apq
300            common/var1/alat1(1024)
400            common/var2/alat2(1024)
500            complex alat1,alat2
600   * lattice=isize**4
700   * inverse temperature=b
800   * subroutine monte(i) gives i monte carlo iterations per link
900   * mup and mdown are dimensioned to isize
1000  * do not run with b=0.
1100           isize=4
1200           b=2.0
1300           nmax=isize
1400           do 5 n=1,nmax
1500           mup(n)=mod(n,isize)+1
1700  5        mdown(n)=mod(n-2+isize,isize)+1
1800           do 6 n=1,5
1900  6        ipower(n)=isize**(n-1)
2000           mf=4*isize**4
2100           do 67 i=1,mf
2200           alat1(i)=1.
2300  67       alat2(i)=0.
2400           call monte(100)
2500           stop
2600           end
2700
2800
2900
3000           subroutine monte(iter)
3100           common/var/b,isize,mdown(4),mup(4),ipower(5),apq
3200           common/var1/alat1(1024)
3300           common/var2/alat2(1024)
3400           complex alat1,alat2
3500           complex uint1,uint2,anew1,anew2
3600           complex a12s1,a26s1,a65s1,a13s1,a34s1,a45s1,a126s1,a134s1
3700           complex a12s2,a26s2,a65s2,a13s2,a34s2,a45s2,a126s2,a134s2
3800           integer x(4)
3900           print*,iter,'iterations'
4000           temp=1./b
4050           iran=1234
4100           do 51 nit=1,iter
4200           sum=0.
4300  * select site
4400           ma=-ipower(2)-ipower(3)-ipower(4)-ipower(5)
4500           do 50 is=1,isize,2
4600           do 50 js=1,isize,2
4700           do 50 ks=1,isize,2
4800           do 50 ls=1,isize,2
4900           x(1)=is+mod(ib,2)
5000           x(2)=js+mod(ib/2,2)
5100           x(3)=ks+mod(ib/4,2)
5200           x(4)=ls+mod(ib/8,2)
5300           m1=ma+is*ipower(1)+js*ipower(2)+ks*ipower(3)+ls*ipower(4)
5400  * select link
5500           do 50 i1=1,4
5600           uint1=0.
5700           uint2=0.
5800  * locate next site in i1 direction
5900           m45=ipower(i1)*(mup(x(i1))-x(i1))
6000           m5=m1+m45
6100           i1ip5=i1*ipower(5)
```

Once I completely understood the program, I began to experiment with it.

```
100   *  lattice
200            common/var/b,isize,mdown(4),mup(4),ipower(5),apq
300            common/var1/alat1(1024)
400            common/var2/alat2(1024)
500            complex alat1,alat2
600   * lattice=isize**4
700   * inverse temperature=b
```

16,384

Once I completely understood the program, I began to

```
      * select site
            ma=-ipower(2)-ipower(3)-ipower(4)-ipower(5)
            do 50 is=1,isize,2
            do 50 js=1,isize,2
            do 50 ks=1,isize,2
            do 50 ls=1,isize,2
            x(1)=is + MOD(IB,2)
            x(2)=js +MOD(IB/2,2)
            x(3)=ks +MOD(IB/4,2)
            x(4)=ls +MOD(IB/8,2)
            m1=ma+is*ipower(1)+js*ipower(2)+ks*ipower(3)+ls*ipower(4)
      * select link
            do 50 i1=1,4
            uint1=0.
```

1050 IB = 0, 15

```
3800        integer x(4)
3900        print*,iter,'iterations'
4000        temp=1./b
4050        iran=1234
4100        do 51 nit=1,iter
4200        sum=0.
4300  * select site
4400        ma=-ipower(2)-ipower(3)-ipower(4)-ipower(5)
4500        do 50 is=1,isize,2
4600        do 50 js=1,isize,2
4700        do 50 ks=1,isize,2
4800        do 50 ls=1,isize,2
4900        x(1)=is + MOD(IB,2)
5000        x(2)=js +MOD(IB/2,2)
5100        x(3)=ks +MOD(IB/4,2)
5200        x(4)=ls +MOD(IB/8,2)
5300        m1=ma+is*ipower(1)+js*ipower(2)+ks*ipower(3)+ls*ipower(4)
5400  * select link
5500        do 50 i1=1,4
5600        uint1=0.
5700        uint2=0.
5800  * locate next site in i1 direction
5900        m45=ipower(i1)*(mup(x(i1))-x(i1))
6000        m5=m1+m45
6100        i1ip5=i1*ipower(5)
```

IB = 0, 15

Go through sites in different order.

```
00100  *  LATTICE SU(2) PROGRAM BASED ON M.CREUTZ'S
00200          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00300          COMMON/VAR1/ALAT1(16384)
00400          COMMON/VAR2/ALAT2(16384)
00500          COMPLEX ALAT1,ALAT2
00600  * LATTICE=ISIZE**4
00700  * INVERSE TEMPERATURE=B
00800  * SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK
00900  * MUP AND MDOWN ARE DIMENSIONED TO ISIZE
01000  * DO NOT RUN WITH B=0.
01100          ISIZE=8
01200          B=2.0
01300          NMAX=ISIZE
01400          DO 5 N=1,NMAX
01500          MUP(N)=MOD(N,ISIZE)+1
01600  5       MDOWN(N)=MOD(N-2+ISIZE,ISIZE)+1
01700          DO 6 N=1,5
01800  6       IPOWER(N)=ISIZE**(N-1)
01900          MF=4*ISIZE**4
02000          DO 67 I=1,MF
02100          ALAT1(I)=1.
02200  67      ALAT2(I)=0.
02300          CALL MONTE(10)
02400          STOP
02500          END
02600
02700
02800
02900          SUBROUTINE MONTE(ITER)
03000          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
03100          COMMON/UPDATE/TEMP,IRAN
03200          INTEGER X(4)
03300          PRINT*,ITER,'ITERATIONS'
03400          TEMP=1./B
03500          IRAN=1234
03600          DO 51 NIT=1,ITER
03700          SUM=0.
03800  *  SELECT SITE
03900          MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)
04000          DO 50 IS=1,ISIZE,4
04100          DO 50 JS=1,ISIZE,4
04200          DO 50 KS=1,ISIZE,4
04300          DO 50 LS=1,ISIZE,4
04350          DO 50 IC=0,15
04400          DO 50 IB=0,15
04500          X(1)=IS+MOD(IB,2)+MOD(IC,2)*2
04600          X(2)=JS+MOD(IB/2,2)+MOD(IC/2,2)*2
04700          X(3)=KS+MOD(IB/4,2)+MOD(IC/4,2)*2
04800          X(4)=LS+MOD(IB/8,2)+MOD(IC/8,2)*2
04900          M1=MA+
05000       C  X(1)*IPOWER(1)+X(2)*IPOWER(2)+X(3)*IPOWER(3)+X(4)*IPOWER(4)
05100  *  SELECT LINK
05200          DO 50 I1=1,4
05300          CALL LINKUPDATE(X,I1,M1,SUM)
05400  50      CONTINUE
05500          APB=1.-SUM/(6*4*ISIZE**4)
05600          PRINT100,ISIZE,B,APB
05700  C       WRITE(25,100) ISIZE,B,APB
05800  100     FORMAT('     ISIZE=',I2,'          GROUP=SU(2)      B=',F6.4,
05900       C                '  AV.PB.=',F6.4)
06000  51      CONTINUE
06100          RETURN
06200          END
06210
06220
```

```
00230
00300          SUBROUTINE LINKUPDATE(X,I1,M1,SUM)
00400          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00500          COMMON/VAR1/ALAT1(16384)
00600          COMMON/VAR2/ALAT2(16384)
00650          COMMON/UPDATE/TEMP,IRAN
00700          COMPLEX ALAT1,ALAT2
00800          COMPLEX UINT1,UINT2,ANEW1,ANEW2
00900          COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1
01000          COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2
01100          INTEGER X(4)
01200          UINT1=0.
01300          UINT2=0.
01400  *  LOCATE NEXT SITE IN I1 DIRECTION
01500          M45=IPOWER(I1)*(MUP(X(I1))-X(I1))
01600          M5=M1+M45
01700          I1IP5=I1*IPOWER(5)
01800          L15=M1+I1IP5
01900  *  LOOP OVER PLANES CONTAINING LINK
02000          DO 1 J2=1,3
02100          I2=MOD(I1+J2-1,4)+1
02200  *LOCATE NEIGHBORING SITES AND LINKS
02300          M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))
02400          M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))
02500          M4=M3+M45
02600          I2IP5=I2*IPOWER(5)
02700          L12=M1+I2IP5
02800          L31=M3+I2IP5
02900          L34=M3+I1IP5
03000          L45=M4+I2IP5
03100          L56=M5+I2IP5
03200          L26=M2+I1IP5
03300  *  OBTAIN INTERACTING SPINS
03400          A12S1=ALAT1(L12)
03500          A26S1=ALAT1(L26)
03600          A34S1=ALAT1(L34)
03700          A45S1=ALAT1(L45)
03800          A65S1=CONJG(ALAT1(L56))
03900          A13S1=CONJG(ALAT1(L31))
04000          A12S2=ALAT2(L12)
04100          A26S2=ALAT2(L26)
04200          A34S2=ALAT2(L34)
04300          A45S2=ALAT2(L45)
04400          A65S2=-(ALAT2(L56))
04500          A13S2=-(ALAT2(L31))
04600  *  MULTIPLY INTERACTING SPINS
04700          A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)
04800          A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)
04900          A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)
05000          A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)
05100          UINT1=UINT1+A126S1*A65S1-A126S2*CONJG(A65S2)
05200       C               +A134S1*A45S1-A134S2*CONJG(A45S2)
05300          UINT2=UINT2+A126S1*A65S2+A126S2*CONJG(A65S1)
05400       C               +A134S1*A45S2+A134S2*CONJG(A45S1)
05500  1       CONTINUE
05600  *SELECT NEW GROUP ELEMENT
05700          UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))   ABS(UINT1)
05800          UMAGIN=1./UMAG
05900          BAG=UMAGIN*TEMP
06000          ONE2B=1.-EXP(-2*B*UMAG)
06100  6       A0=1.+ALOG(1.-ONE2B*RAN(IRAN))*BAG
06200          RAD=1.-A0**2
06300          IF(RAN(IRAN)**2.GT.RAD)GO TO 6
06400          A3=SQRT(RAD)*(2*RAN(IRAN)-1.)
```

```
*  LATTICE SU(2) PROGRAM BASED ON M.CREUTZ'S
         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APQ
         COMMON/VAR1/ALAT1(16384)
         COMMON/VAR2/ALAT2(16384)
         COMPLEX ALAT1,ALAT2
*  LATTICE=ISIZE**4
*  INVERSE TEMPERATURE=B
*  SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK
*  MUP
*  DO
```

Note high degree of intellectual probity.
Gives credit but not blame to original author.

```
*  LATTICE SU(2) PROGRAM BASED ON M.CREUTZ'S
         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APQ
         COMMON/VAR1/ALAT1(16384)
         COMMON/VAR2/ALAT2(16384)
         COMPLEX ALAT1,ALAT2
*  LATTICE=ISIZE**4
*  INVERSE TEMPERATURE=
*  SUBROUTINE MONTE(I)
*  MUP AND MDOWN ARE DI
*  DO NOT RUN WITH B=0.
         ISIZE=8
         B=2.0
         NMAX=ISIZE
         DO 5 N=1,NMAX
         MUP(N)=MOD(N+
5        MDOWN(N)=MOD(
         DO 6 N=1,5
6        IPOWER(N)=ISI
         MF=4*ISIZE**4
         DO 67 I=1,MF
         ALAT1(I)=1.
67       ALAT2(I)=0.
         CALL MONTE(10)
         STOP
         END

         SUBROUTINE MON
         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(
         COMMON/UPDATE/TEMP,IRAN
         INTEGER X(4)
         PRINT*,ITER,'ITERATIONS'
         TEMP=1./B
         IRAN=1234
         DO 51 NIT=1,ITER
         SUM=0.
*  SELECT SITE
         MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)
         DO 50 IS=1,ISIZE,4
         DO 50 JS=1,ISIZE,4
         DO 50 KS=1,ISIZE,4
         DO 50 LS=1,ISIZE,4
         DO 50 IC=0,15
         DO 50 IB=0,15
         X(1)=IS+MOD(IB,2)+MOD(IC,2)*2
         X(2)=JS+MOD(IB/2,2)+MOD(IC/2,2)*2
         X(3)=KS+MOD(IB/4,2)+MOD(IC/4,2)*2
         X(4)=LS+MOD(IB/8,2)+MOD(IC/8,2)*2
         M1=MA+
      C  X(1)*IPOWER(1)+X(2)*IPOWER(2)+X(3)*IPOWER(3)+X(4)*IPOWER(4)
*  SELECT LINK
         DO 50 I1=1,4
         CALL LINKUPDATE(X,I1,M1,SUM)
50       CONTINUE
         APQ=1.-SUM/(6*4*ISIZE**4)
         PRINT100,ISIZE,B,APQ
C        WRITE(25,100) ISIZE,B,APQ
100      FORMAT('    ISIZE=',I2,'          GROUP=SU(2)        B=',F6.4,
      C          '    AV.PQ.=',F6.4)
51       CONTINUE
         RETURN
         END
```

```
         SUBROUTINE LINKUPDATE(X,I1,M1,SUM)
         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APQ
         COMMON/VAR1/ALAT1(16384)
         COMMON/VAR2/ALAT2(16384)
```

```
         L26=M2+I1IP5
*  OBTAIN INTERACTING SPINS
         A12S1=ALAT1(L12)
         A26S1=ALAT1(L26)
         A34S1=ALAT1(L34)
         A45S1=ALAT1(L45)
         A65S1=CONJG(ALAT1(L56))
         A13S1=CONJG(ALAT1(L31))
         A12S2=ALAT2(L12)
         A26S2=ALAT2(L26)
         A34S2=ALAT2(L34)
         A45S2=ALAT2(L45)
         A65S2=-(ALAT2(L56))
         A13S2=-(ALAT2(L31))
*  MULTIPLY INTERACTING SPINS
         A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)
         A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)
         A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)
         A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)
         UINT1=UINT1+A126S1*A65S1-A126S2*CONJG(A65S2)
      C              +A134S1*A45S1-A134S2*CONJG(A45S2)
         UINT2=UINT2+A126S1*A65S2+A126S2*CONJG(A65S1)
      C              +A134S1*A45S2+A134S2*CONJG(A45S1)
1        CONTINUE
*SELECT NEW GROUP ELEMENT
         UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))   ABS(UINTS)
         UMAGIN=1./UMAG
         BAG=UMAGIN*TEMP
         OME2B=1.-EXP(-2*B*UMAG)
6        A0=1.+ALOG(1.-OME2B*RAN(IRAN))*BAG
         RAD=1.-A0**2
         IF(RAN(IRAN)**2.GT.RAD)GO TO 6
         A3=SQRT(RAD)*(2*RAN(IRAN)-1.)
```

```
00100  *  LATTICE SU(2) PROGRAM BASED ON M.CREUTZ'S
00200          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00300          COMMON/VAR1/ALAT1(16384)
00400          COMMON/VAR2/ALAT2(16384)
00500          COMPLEX ALAT1,ALAT2
00600  * LATTICE=ISIZE**4
00700  * INVERSE TEMPERATURE=B
00800  * SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK
00900  * MUP AND MDOWN ARE DIMENSIONED TO ISIZE
01000  * DO NOT RUN WITH B=0.
01100          ISIZE=8
01200          B=2.0
01300          NMAX=ISIZE
01400          DO 5 N=1,NMAX
01500          MUP(N)=MOD(N,ISIZE)+1
01600  5       MDOWN(N)=MOD(N-2+ISIZE,ISIZE)+1
01700          DO 6 N=1,5
01800  6       IPOWER(N)=ISIZE**(N-1)
01900          MF=4*ISIZE**4
02000          DO 67 I=1,MF
02100          ALAT1(I)=1.
02200  67      ALAT2(I)=0.
02300          CALL MONTE(10)
02400          STOP
02500          END
02600
02700
02800
02900          SUBROUTINE MONTE(ITER)
03000          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
03100          COMMON/UPDATE/TEMP,IRAN
03200          INTEGER X(4)
03300          PRINT*,ITER,'ITERATIONS'
03400          TEMP=1./B
03500          IRAN=1234
03600          DO 51 NIT=1,ITER
03700          SUM=0.
03800  *  SELECT SITE
03900          MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)
04000          DO 50 IS=1,ISIZE,4
04100          DO 50 JS=1,ISIZE,4
04200          DO 50 KS=1,ISIZE,4
04300          DO 50 LS=1,ISIZE,4
04350          DO 50 IC=0,15
04400          DO 50 IB=0,15
04500          X(1)=IS+MOD(IB,2)+MOD(IC,2)*2
04600          X(2)=JS+MOD(IB/2,2)+MOD(IC/2,2)*2
04700          X(3)=KS+MOD(IB/4,2)+MOD(IC/4,2)*2
04800          X(4)=LS+MOD(IB/8,2)+MOD(IC/8,2)*2
04900          M1=MA+
05000       C  X(1)*IPOWER(1)+X(2)*IPOWER(2)+X(3)*IPOWER(3)+X(4)*IPOWER(4)
05100  *  SELECT LINK
05200          DO 50 I1=1,4
05300          CALL LINKUPDATE(X,I1,M1,SUM)
05400  50      CONTINUE
05500          APB=1.-SUM/(6*4*ISIZE**4)
05600          PRINT100,ISIZE,B,APB
05700  C       WRITE(25,100) ISIZE,B,APB
05800  100     FORMAT('     ISIZE=',I2,'          GROUP=SU(2)      B=',F6.4,
05900       C                '  AV.PB.=',F6.4)
06000  51      CONTINUE
06100          RETURN
06200          END
06210
06220
```

```
00230
00300          SUBROUTINE LINKUPDATE(X,I1,M1,SUM)
00400          COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00500          COMMON/VAR1/ALAT1(16384)
00600          COMMON/VAR2/ALAT2(16384)
00650          COMMON/UPDATE/TEMP,IRAN
00700          COMPLEX ALAT1,ALAT2
00800          COMPLEX UINT1,UINT2,ANEW1,ANEW2
00900          COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1
01000          COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2
01100          INTEGER X(4)
01200          UINT1=0.
01300          UINT2=0.
01400  *  LOCATE NEXT SITE IN I1 DIRECTION
01500          M45=IPOWER(I1)*(MUP(X(I1))-X(I1))
01600          M5=M1+M45
01700          I1IP5=I1*IPOWER(5)
01800          L15=M1+I1IP5
01900  *  LOOP OVER PLANES CONTAINING LINK
02000          DO 1 J2=1,3
02100          I2=MOD(I1+J2-1,4)+1
02200  *LOCATE NEIGHBORING SITES AND LINKS
02300          M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))
02400          M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))
02500          M4=M3+M45
02600          I2IP5=I2*IPOWER(5)
02700          L12=M1+I2IP5
02800          L31=M3+I2IP5
02900          L34=M3+I1IP5
03000          L45=M4+I2IP5
03100          L56=M5+I2IP5
03200          L26=M2+I1IP5
03300  *  OBTAIN INTERACTING SPINS
03400          A12S1=ALAT1(L12)
03500          A26S1=ALAT1(L26)
03600          A34S1=ALAT1(L34)
03700          A45S1=ALAT1(L45)
03800          A65S1=CONJG(ALAT1(L56))
03900          A13S1=CONJG(ALAT1(L31))
04000          A12S2=ALAT2(L12)
04100          A26S2=ALAT2(L26)
04200          A34S2=ALAT2(L34)
04300          A45S2=ALAT2(L45)
04400          A65S2=-(ALAT2(L56))
04500          A13S2=-(ALAT2(L31))
04600  *  MULTIPLY INTERACTING SPINS
04700          A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)
04800          A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)
04900          A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)
05000          A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)
05100          UINT1=UINT1+A126S1*A65S1-A126S2*CONJG(A65S2)
05200       C               +A134S1*A45S1-A134S2*CONJG(A45S2)
05300          UINT2=UINT2+A126S1*A65S2+A126S2*CONJG(A65S1)
05400       C               +A134S1*A45S2+A134S2*CONJG(A45S1)
05500  1       CONTINUE
05600  *SELECT NEW GROUP ELEMENT
05700          UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))   ABS(UINT1)
05800          UMAGIN=1./UMAG
05900          BAG=UMAGIN*TEMP
06000          ONE2B=1.-EXP(-2*B*UMAG)
06100  6       A0=1.+ALOG(1.-ONE2B*RAN(IRAN))*BAG
06200          RAD=1.-A0**2
06300          IF(RAN(IRAN)**2.GT.RAD)GO TO 6
06400          A3=SQRT(RAD)*(2*RAN(IRAN)-1.)
```

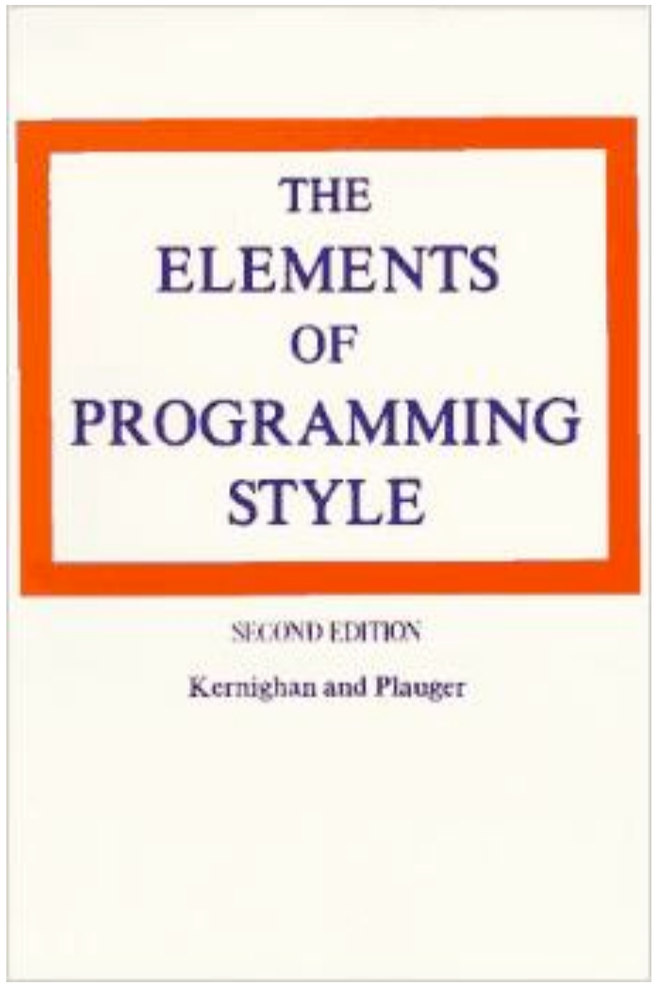
```
00100 *  LATTICE SU(2) PROGRAM BASED ON M.CREUTZ'S
00200         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00300         COMMON/VAR1/ALAT1(16384)
00400         COMMON/VAR2/ALAT2(16384)
00500         COMPLEX ALAT1,ALAT2
00600 * LATTICE=ISIZE**4
00700 * INVERSE TEMPERATURE=B
00800 * SUBROUTINE MONTE(I) GIVES I MONTE CARLO ITERATIONS PER LINK
00900 * MUP AND MDOWN ARE DIMENSIONED TO ISIZE
01000 * DO NOT RUN WITH B=0.
01100         ISIZE=8
01200         B=2.0
01300         NMAX=ISIZE
01400         DO 5 N=1,NMAX
01500         MUP(N)=MOD(N,ISIZE)+1
01600 5       MDOWN(N)=MOD(N-2+ISIZE,ISIZE)+1
01700         DO 6 N=1,5
01800 6       IPOWER(N)=ISIZE**(N-1)
01900         MF=4*ISIZE**4
02000         DO 67 I=1,MF
02100         ALAT1(I)=1.
02200 67      ALAT2(I)=0.
02300         CALL MONTE(10)
02400         STOP
02500         END
02600
02700
02800
02900         SUBROUTINE MONTE(ITER)
03000         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
03100         COMMON/UPDATE/TEMP,IRAN
03200         INTEGER X(4)
03300         PRINT*,ITER,'ITERATIONS'
03400         TEMP=1./B
03500         IRAN=1234
03600         DO 51 NIT=1,ITER
03700         SUM=0.
```

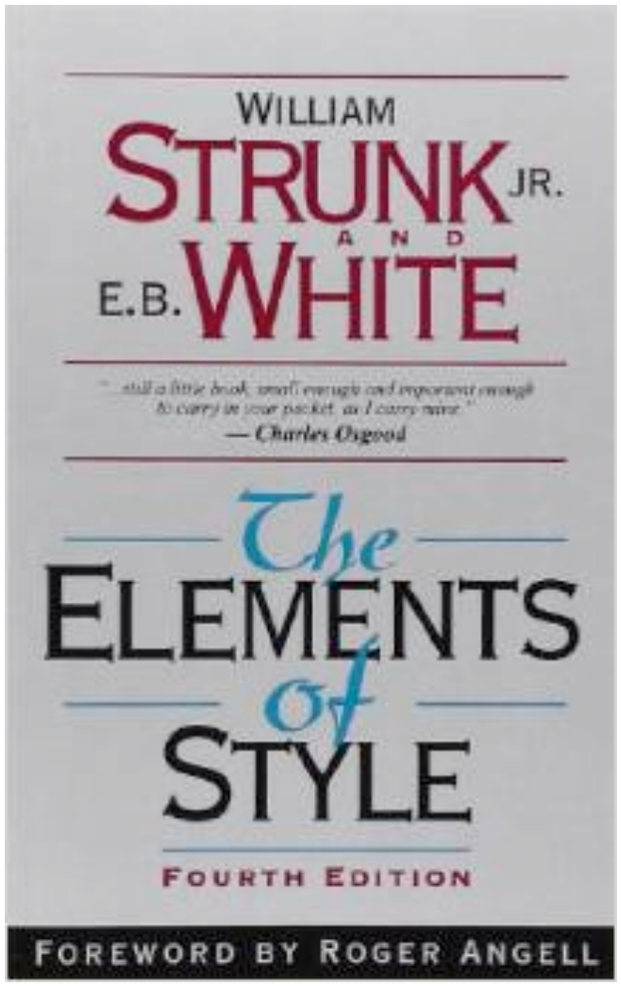
If any of you talks to my wife, could you tell her that I have all of those boxes of stuff in the basement from grad school and postdocs stored for scientific purposes, and not because I'm too lazy to sort through them?

```
00230
00300         SUBROUTINE LINKUPDATE(X,I1,M1,SUM)
00400         COMMON/VAR/B,ISIZE,MDOWN(8),MUP(8),IPOWER(5),APB
00500         COMMON/VAR1/ALAT1(16384)
00600         COMMON/VAR2/ALAT2(16384)
00650         COMMON/UPDATE/TEMP,IRAN
00700         COMPLEX ALAT1,ALAT2
00800         COMPLEX UINT1,UINT2,ANEW1,ANEW2
00900         COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1
07000         COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2
07100         INTEGER X(4)
07200         UINT1=0.
07300         UINT2=0.
07400 * LOCATE NEXT SITE IN I1 DIRECTION
07500         M45=IPOWER(I1)*(MUP(X(I1))-X(I1))
07600         M5=M1+M45
07700         I1IP5=I1*IPOWER(5)
07800         L15=M1+I1IP5
07900 * LOOP OVER PLANES CONTAINING LINK
08000         DO 1 J2=1,3
08100         I2=MOD(I1+J2-1,4)+1
08200 *LOCATE NEIGHBORING SITES AND LINKS
08300         M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))
08400         M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))
08500         M4=M3+M45
08600         I2IP5=I2*IPOWER(5)
08700         L12=M1+I2IP5
08800         L31=M3+I2IP5
08900         L34=M3+I1IP5
09000         L45=M4+I2IP5
09100         L56=M5+I2IP5
09200         L26=M2+I1IP5
09300 * OBTAIN INTERACTING SPINS
09400         A12S1=ALAT1(L12)
09500         A26S1=ALAT1(L26)
09600         A34S1=ALAT1(L34)
09700         A45S1=ALAT1(L45)
09800         A65S1=CONJG(ALAT1(L56))
09900         A13S1=CONJG(ALAT1(L31))
10000         A12S2=ALAT2(L12)
10100         A26S2=ALAT2(L26)
10200         A34S2=ALAT2(L34)
10300         A45S2=ALAT2(L45)
10400         A65S2=-(ALAT2(L56))
10500         A13S2=-(ALAT2(L31))
10600 * MULTIPLY INTERACTING SPINS
10700         A126S1=A12S1*A26S1-A12S2*CONJG(A26S2)
10800         A126S2=A12S1*A26S2+A12S2*CONJG(A26S1)
10900         A134S1=A13S1*A34S1-A13S2*CONJG(A34S2)
11000         A134S2=A13S1*A34S2+A13S2*CONJG(A34S1)
11100         UINT1=UINT1+A126S1*A65S1-A126S2*CONJG(A65S2)
11200      C             +A134S1*A45S1-A134S2*CONJG(A45S2)
11300         UINT2=UINT2+A126S1*A65S2+A126S2*CONJG(A65S1)
11400      C             +A134S1*A45S2+A134S2*CONJG(A45S1)
11500 1       CONTINUE
11600 *SELECT NEW GROUP ELEMENT
11700         UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))   ABS(UINT1)
11800         UMAGIN=1./UMAG
11900         BAG=UMAGIN*TEMP
12000         ONE2B=1.-EXP(-2*B*UMAG)
12100 6       A0=1.+ALOG(1.-ONE2B*RAN(IRAN))*BAG
12200         RAD=1.-A0**2
12300         IF(RAN(IRAN)**2.GT.RAD)GO TO 6
12400         A3=SQRT(RAD)*(2*RAN(IRAN)-1.)
```

Programming style

What made the SU(2) program so useful as a tutorial?





Kernighan and Plauger's *Elements of Programming Style* has much good advice about programming. Mike's program exemplifies many of the simple rules it recommends.

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     000155
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
C* LATTIC
C* INVERS
C* SUBROU
C*MUP AND
C*DO NOT
      IS
      B=
      NM
      DE
      ML
5     ME
      DO
6     IF
      MF
      DE
      AL
67    AE
      CA
      STOP$END                                                          000560
                                                                        000570
      SUBROUTINE MONTE(ITER)                                            000580
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000590
      COMMON/VAR1/ALAT1(40000)                                          000600
      COMMON/VAR2/ALAT2(40000)                                          000610
      LEVEL2,ALAT1,ALAT2                                                000620
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000630
      COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1         000640
      COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2         000650
      INTEGER X(4)                                                      000660
      PRINT*,ITER,"ITERATION(S)"                                        000670
      TEMP=1/B                                                          000680
      DO51NIT=1,ITER                                                    000690
      SUM=0                                                             000700
C*SITE LOOPS                                                            000710
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000720
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000730
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000740
      DO50KS=1,ISIZE$X(3)=KS$MD                                         000750
      DO50LS=1,ISIZE$X(4)=LS$M1
C*SELECT LINK
      DO 50 I1=1,4
      UINT1=UINT2=0
C*LOCATE NEXT SITE IN I1 DIRECTI
      M45=IPOWER(I1)*(MUP(X(I1)
      M5=M1+M45
      I1IP5=I1*IPOWER(5)
      L15=M1+I1IP5
C*LOOP OVER PLANES CONTAINING LI
      DO1J2=1,3$I2=MOD(I1+J2-1,
C*LOCATE NEIGHBORING SITES AND L
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000900
      M4=M3+M45                                                         000910
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
      L34=M3+I1IP5                                                      000950
      L45=M4+I2IP5                                                      000960
      L56=M5+I2IP5                                                      000970
                                                                        000980
                                                                        000990
                                                                        001000
                                                                        001010
                                                                        001020
                                                                        001030
                                                                        001040
                                                                        001050
                                                                        001060
                                                                        001070
                                                                        001080
                                                                        001090
                                                                        001100
                                                                        001110
                                                                        001120
                                                                        001130
                                                                        001140
                                                                        001150
      C   +A126S2*CONJG(A65S1)                                          001160
      C   +A134S1*A45S2                                                001170
      C   +A134S2*CONJG(A45S1)                                         001180
1     CONTINUE                                                          001190
*SELECT NEW GROUP ELEMENT                                               001200
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001210
      UMAGIN=1/UMAG                                                     001220
      BAG=UMAGIN*TEMP                                                   001230
      OME2B=1-EXP(-2*B*UMAG)                                            001240
6     A0=1.+ALOG(1.-OME2B*RANF(0))*BAG                                  001250
      RAD=1-A0**2                                                       001260
      IF(RANF(0)**2.GT.RAD)GOTO6                                        001270
      A3=SQRT(RAD)*(2*RANF(0)-1.)                                       001280
8     A1=RANF(0)-.5$A2=RANF(0)-.5                                       001290
      AMAG=A1**2+A2**2                                                  001300
      IF(AMAG.GT..25)GOTO8                                              001310
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001320
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001330
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001340
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001350
      SUM=SUM+A0*UMAG
```

Write clearly — don't be too clever. K&P

16. Be clear S&W

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                    000155
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ               000160
      COMMON/VAR1/ALAT1(40000)                                         000170
      COMMON/VAR2/ALAT2(40000)                                         000180
      LEVEL2,ALAT1,ALAT2                                               000190
      COMPLEX ALAT1,ALAT2                                              000200
C* LATTIC
C* INVERS
C* SUBROU
C*MUP AND
C*DO NOT
      IS
      B=
      NM
      DE
      ML
5     ME
      DO
6     IF
      MF
      DE
      AL
67    AB
      CA
      STOP$E

      SUBROU
      COMMON
      COMMON
      COMMON
      LEVEL2
      COMPLE
      COMPLE
      COMPLE
      INTEGE
      PRINT*
      TEMP=1.
      DO51NI
      SUM=0
C*SITE LOOPS                                                           000720
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                      000730
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                        000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                        000750
      DO50KS=1,ISIZE$X(3)=KS$MD
      DO50LS=1,ISIZE$X(4)=LS$M1
C*SELECT LINK
      DO 50 I1=1,4
      UINT1=UINT2=0
C*LOCATE NEXT SITE IN I1 DIRECTI
      M45=IPOWER(I1)*(MUP(X(I1)
      M5=M1+M45
      I1IP5=I1*IPOWER(5)
      L15=M1+I1IP5
C*LOOP OVER PLANES CONTAINING LI
      DO1J2=1,3$I2=MOD(I1+J2-1,
C*LOCATE NEIGHBORING SITES AND L
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                              000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                            000900
      M4=M3+M45                                                        000910
      I2IP5=I2*IPOWER(5)                                               000920
      L12=M1+I2IP5                                                     000930
      L31=M3+I2IP5                                                     000940
      L34=M3+I1IP5
      L45=M4+I2IP5
      L56=M5+I2IP5
                                                                       000950
                                                                       000960
                                                                       000970
                                                                       000980
                                                                       000990
                                                                       001000
                                                                       001010
                                                                       001020
                                                                       001030
                                                                       001040
                                                                       001050
                                                                       001060
                                                                       001070
                                                                       001080
                                                                       001090
                                                                       001100
                                                                       001110
                                                                       001120
                                                                       001130
                                                                       001140
                                                                       001150
                                                                       001160
                                                                       001170
                                                                       001180
                                                                       001190
                                                                       001200
                                                                       001210
                                                                       001220
                                                                       001230
                                                                       001240
                                                                       001250
                                                                       001260
                                                                       001270
                                                                       001280
                                                                       001290
                                                                       001300
                                                                       001310
                                                                       001320
                                                                       001330
                                                                       001340
                                                                       001350
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)
      SUM=SUM+A0*UMAG
```

Write clearly — don't be too clever. K&P

Use library functions. K&P

16. Be clear S&W

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     00015
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX
* LATTICE=ISI
* INVERSE TEM
* SUBROUTINE
*MUP AND MDOW
*DO NOT RUN W
      ISIZE=1
      B=2.6
      NMAX=IS
      DO5N=1,
      MUP(N)=
5     MDOWN(N
      DO6N=1,
6     IPOWER(
      MF=4*IS
      DO67M=1
      ALAT1(M
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
      SUBROUTINE MONTE(ITER)                                            000580
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000590
      COMMC
      COMMC
      LEVEL
      COMPL
      COMPL
      COMPL
      INTEGER X(4)                                                      000660
      PRINT*,ITER,"ITERATION(S)"                                        000670
      TEMP
      DO51
      SUM=
*SITE LOOP
      MA=
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000750
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000760
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000770
*SELECT LINK                                                            000780
      DO 50 I1=1,4                                                      000790
      UINT1=UINT2=0                                                     000800
*LOCATE NEXT SITE IN I1 DIRECTION                                       000810
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))                                 000820
      M5=M1+M45                                                         000830
      I1IP5=I1*IPOWER(5)                                                000840
      L15=M1+I1IP5                                                      000850
*LOOP OVER PLANES CONTAINING LINK                                       000860
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1                                     000870
*LOCATE NEIGHBORING SITES AND LINKS                                     000880
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000900
      M4=M3+M45                                                         000910
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
      L34=M3+I1IP5                                                      000950
      L45=M4+I2IP5                                                      000960
                                                                        000970
                                                                        000980
                                                                        000990
                                                                        001000
                                                                        001010
                                                                        001020
                                                                        001030
                                                                        001040
                                                                        001050
                                                                        001060
                                                                        001070
                                                                        001080
                                                                        001090
                                                                        001100
                                                                        001110
                                                                        001120
                                                                        001130
      C   +A134S2*CONJG(A45S2)                                         001140
      UINT2=UINT2+A126S1*A65S2                                          001150
      C   +A126S2*CONJG(A65S1)                                         001160
      C   +A134S1*A45S2                                                001170
      C   +A134S2*CONJG(A45S1)                                         001180
1     CONTINUE                                                          001190
*SELECT NEW GROUP ELEMENT                                               001200
                                                                        001210
                                                                        001220
                                                                        001230
                                                                        001240
                                                                        001250
      IF(RANF(0)**2.GT.RAD)GOTO6                                        001260
      A3=SQRT(RAD)*(2*RANF(0)-1.)                                       001270
                                                                        001280
                                                                        001290
                                                                        001300
                                                                        001310
                                                                        001320
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001330
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001340
      SUM=SUM+A0*UMAG                                                   001350
50    CONTINUE                                                          001360
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001370
      PRINT100,ISIZE,B,APQ                                              001380
100   FORMAT("     ISIZE=",I2,"    GROUP=SU(2)",                        001390
     CONT  "    B=",F6.4,"    AV.PQ.=",F6.4)                           001400
51    CONTINUE                                                          001410
      RETURN                                                            001420
      END                                                               001430
                                                                        001440
```

Don't over-comment. K&P

11. Do not explain too much

17. Omit needless words S&W

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     000150
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
*  LATTICE=
*  INVERSE
*  SUBROUTI
*MUP AND MI
*DO NOT RUI
      ISIZ
      B=2.
      NMAX=
      DO5N
      MUP(1
5     MDOWI
      DO6N=
6     IPOWI
      MF=4
      DO67I
      ALAT
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
      SUBROUTINE MONTE(ITER)                                            000580
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000590
      COMMON/VAR1/ALAT1(40000)                                          000600
      COMMON/VAR2/ALAT2(40000)                                          000610
      LEVEL2,ALAT1,ALAT2                                                000620
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000630
      COMPLEX A12S1,A26S1,A65S1,A13S1,A34S1,A45S1,A126S1,A134S1         000640
      COMPLEX A12S2,A26S2,A65S2,A13S2,A34S2,A45S2,A126S2,A134S2         000650
      INTEGER X(4)                                                      000660
      PRINT*,ITER,"ITERATION(S)"                                        000670
      TEMP=1/B                                                          000680
      DO51NIT=1,ITER                                                    000690
      SUM=0                                                             000700
*SITE LOOPS                                                            000710
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000720
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000730
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000740
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000750
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000760
*SELECT LINK                                                           000770
      DO 50 I1=1,4                                                      000780
      UINT1=UINT2=0                                                     000790
*LOCATE NEXT SITE IN I1 DIRECTION                                      000800
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))                                 000810
      M5=M1+M45                                                         000820
      I1IP5=I1*IPOWER(5)                                                000830
      L15=M1+I1IP5                                                      000840
*LOOP OVER PLANES CONTAINING LINK                                      000850
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1                                     000860
*LOCATE NEIGHBORING SITES AND LINKS                                    000870
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000880
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000890
      M4=M3+M45                                                         000900
      I2IP5=I2*IPOWER(5)                                                000910
      L12=M1+I2IP5                                                      000920
      L31=M3+I2IP5                                                      000930
      L34=M3+I1IP5                                                      000940
      L45=M4+I2IP5                                                      000950
      L56=M5+I2IP5                                                      000960
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                                                                        000980
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                                                                        001070
                                                                        001080
                                                                        001090
                                                                        001100
                                                                        001110
                                                                        001120
      C  -A134S2*CONJG(A45S2)                                           001130
      UINT2=UINT2+A126S1*A65S2                                          001140
      C  +A126S2*CONJG(A65S1)                                           001150
      C  +A134S1*A45S2                                                  001160
      C  +A134S2*CONJG(A45S1)                                           001170
1     CONTINUE                                                          001180
*SELECT NEW GROUP ELEMENT                                              001190
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001200
      UMAGIN=1/UMAG                                                     001210
      BAG=UMAGIN*TEMP                                                   001220
      OME2B=1-EXP(-2*B*UMAG)                                            001230
6     A0=1.+ALOG(1.-OME2B*RANF(0))*BAG                                  001240
      RAD=1-A0**2                                                       001250
      IF(RANF(0)**2.GT.RAD)GOTO6                                        001260
      A3=SQRT(RAD)*(2*RANF(0)-1.)                                       001270
8     A1=RANF(0)-.5$A2=RANF(0)-.5                                       001280
      AMAG=A1**2+A2**2                                                  001290
      IF(AMAG.GT..25)GOTO8                                              001300
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001310
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001320
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001330
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001340
      SUM=SUM+A0*UMAG                                                   001350
50    CONTINUE                                                          001360
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001370
      PRINT100,ISIZE,B,APQ                                              001380
100   FORMAT("     ISIZE=",I2,"    GROUP=SU(2)",                        001390
     CONT  "    B=",F6.4,"    AV.PQ.=",F6.4)                           001400
51    CONTINUE                                                          001410
      RETURN                                                            001420
      END                                                               001430
                                                                        001440
```

Use variable names that mean something. K&P

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     000150
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
* LATTICE=
* INVERSE
* SUBROUTI
*MUP AND MI
*DO NOT RUI
      ISIZ
      B=2.
      NMAX=
      DO5N
      MUP(1
5     MDOWI
      DO6N=
6     IPOWI
      MF=4
      DO67I
      ALAT
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
                                                                        000580
      SUBROUTINE MONTE(ITER)                                            000590
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000600
      COMMON/VAR1/ALAT1(40000)                                          000610
      COMMON/VAR2/ALAT2(40000)                                          000620
      LEVEL2,ALAT1,ALAT2                                                000630
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000640
      COMPLEX A12S1,A26S1,A65S1,A13S
      COMPLEX A12S2,A26S2,A65S2,A13S
      INTEGER X(4)
      PRINT*,ITER,"ITERATION(S)"
      TEMP=1/B
      DO51NIT=1,ITER
      SUM=0                                                             000710
*SITE LOOPS                                                             000720
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000730
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000750
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000760
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000770
*SELECT LINK                                                            000780
      DO 50 I1=1,4                                                      000790
      UINT1=UINT2=0                                                     000800
*LOCATE NEXT SITE IN I1 DIRECTION                                       000810
      M45=IPOWER(I1)*(MUP(X(I1))-X(I1))                                 000820
      M5=M1+M45                                                         000830
      I1IP5=I1*IPOWER(5)                                                000840
      L15=M1+I1IP5                                                      000850
*LOOP OVER PLANES CONTAINING LINK                                       000860
      DO1J2=1,3$I2=MOD(I1+J2-1,4)+1                                     000870
*LOCATE NEIGHBORING SITES AND LINKS                                     000880
      M2=M1+IPOWER(I2)*(MUP(X(I2))-X(I2))                               000890
      M3=M1+IPOWER(I2)*(MDOWN(X(I2))-X(I2))                             000900
      M4=M3+M45                                                         000910
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
      L34=M3+I1IP5                                                      000950
      L45=M4+I2IP5                                                      000960
      L56=M5+I2IP5                                                      000970
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                                                                        001080
                                                                        001090
                                                                        001100
                                                                        001110
                                                                        001120
      C  -A13452*CONJG(A45S2)                                           001130
      UINT2=UINT2+A126S1*A65S2                                          001140
      C  +A126S2*CONJG(A65S1)                                           001150
      C  +A134S1*A45S2                                                  001160
      C  +A134S2*CONJG(A45S1)                                           001170
1     CONTINUE                                                          001180
*SELECT NEW GROUP ELEMENT                                               001190
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001200
      UMAGIN=1/UMAG                                                     001210
      BAG=UMAGIN*TEMP                                                   001220
      OME2B=1-EXP(-2*B*UMAG)                                            001230
                                                                        001240
                                                                        001250
                                                                        001260
                                                                        001270
                                                                        001280
                                                                        001290
                                                                        001300
                                                                        001310
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001320
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001330
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001340
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001350
      SUM=SUM+A0*UMAG                                                   001360
50    CONTINUE                                                          001370
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001380
      PRINT100,ISIZE,B,APQ                                              001390
100   FORMAT("     ISIZE=",I2,"    GROUP=SU(2)",                        001400
     CONT  "    B=",F6.4,"    AV.PQ.=",F6.4)                           001410
51    CONTINUE                                                          001420
      RETURN                                                            001430
      END                                                               001440
```

Use variable names that mean something. K&P

Lots of other examples...

Programming style

```
      PROGRAM LATTICE(INPUT,OUTPUT)                                     00015
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000160
      COMMON/VAR1/ALAT1(40000)                                          000170
      COMMON/VAR2/ALAT2(40000)                                          000180
      LEVEL2,ALAT1,ALAT2                                                000190
      COMPLEX ALAT1,ALAT2                                               000200
* LATTICE=
* INVERSE
* SUBROUTI
*MUP AND MI
*DO NOT RUI
      ISIZI
      B=2.
      NMAX=
      DO5N=
      MUP(1
5     MDOWI
      DO6N=
6     IPOWI
      MF=4
      DO67I
      ALAT
67    ALAT2(M)=0                                                        000400
      CALL MONTE(30)                                                    000410
      STOP$END                                                          000560
                                                                        000570
                                                                        000580
      SUBROUTINE MONTE(ITER)                                            000590
      COMMON/VAR/B,ISIZE,MDOWN(10),MUP(10),IPOWER(5),APQ                000600
      COMMON/VAR1/ALAT1(40000)                                          000610
      COMMON/VAR2/ALAT2(40000)                                          000620
      LEVEL2,ALAT1,ALAT2                                                000630
      COMPLEX ALAT1,ALAT2,UINT1,UINT2,ANEW1,ANEW2                       000640
      COMPLEX A12S1,A26S1,A65S1,A13S
      COMPLEX A12S2,A26S2,A65S2,A13S
      INTEGER X(4)
      PRINT*,ITER,"ITERATION(S)"
      TEMP=1/B
      DO51NIT=1,ITER
      SUM=0                                                             000710
*SITE LOOPS                                                             000720
      MA=-IPOWER(2)-IPOWER(3)-IPOWER(4)-IPOWER(5)                       000730
      DO50IS=1,ISIZE$X(1)=IS$MB=MA+IS*IPOWER(1)                         000740
      DO50JS=1,ISIZE$X(2)=JS$MC=MB+JS*IPOWER(2)                         000750
      DO50KS=1,ISIZE$X(3)=KS$MD=MC+KS*IPOWER(3)                         000760
      DO50LS=1,ISIZE$X(4)=LS$M1=MD+LS*IPOWER(4)                         000770
*SELECT LINK                                                            000780
      DO 50 I1=1,4                                                      000790
      UINT1=UINT2=0                                                     000800
*LOCATE NEXT SITE IN I1 DIRECTION                                       000810
      M45=IPOWER(I1)*(MUP(X(I
      M5=M1+M45
      I1IP5=I1*IPOWER(5)
      L15=M1+I1IP5
*LOOP OVER PLANES CONTAINING
      DO1J2=1,3$I2=MOD(I1+J2-
*LOCATE NEIGHBORING SITES ANE
      M2=M1+IPOWER(I2)*(MUP(X
      M3=M1+IPOWER(I2)*(MDOWN
      M4=M3+M45
      I2IP5=I2*IPOWER(5)                                                000920
      L12=M1+I2IP5                                                      000930
      L31=M3+I2IP5                                                      000940
      L34=M3+I1IP5
      L45=M4+I2IP5
      L56=M5+I2IP5                                                      000950
                                                                        000960
                                                                        000970
                                                                        000980
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                                                                        001080
                                                                        001090
                                                                        001100
                                                                        001110
                                                                        001120
      C   -A13452*CONJG(A45S2)                                         001130
      UINT2=UINT2+A126S1*A65S2                                          001140
      C   +A126S2*CONJG(A65S1)                                         001150
      C   +A134S1*A45S2                                                001160
      C   +A134S2*CONJG(A45S1)                                         001170
1     CONTINUE                                                          001180
*SELECT NEW GROUP ELEMENT                                               001190
      UMAG=SQRT(REAL(UINT1*CONJG(UINT1)+UINT2*CONJG(UINT2)))            001200
      UMAGIN=1/UMAG                                                     001210
      BAG=UMAGIN*TEMP                                                   001220
      OME2B=1-EXP(-2*B*UMAG)                                            001230
                                                                        001240
                                                                        001250
                                                                        001260
                                                                        001270
                                                                        001280
                                                                        001290
                                                                        001300
                                                                        001310
      ANEW1=CMPLX(A0,A3)*UMAGIN                                         001320
      ANEW2=CMPLX(A2,A1)*(UMAGIN*SQRT((1.-A0**2-A3**2)/AMAG))           001330
      ALAT1(L15)=ANEW1*UINT1-ANEW2*CONJG(UINT2)                         001340
      ALAT2(L15)=ANEW1*UINT2+ANEW2*CONJG(UINT1)                         001350
      SUM=SUM+A0*UMAG                                                   001360
50    CONTINUE                                                          001370
      APQ=1.-SUM/(6.*4.*ISIZE**4)                                       001380
      PRINT100,ISIZE,B,APQ                                              001390
100   FORMAT("      ISIZE=",I2,"     GROUP=SU(2)",                      001400
     CONT  "     B=",F6.4,"     AV.PQ.=",F6.4)                         001410
51    CONTINUE                                                          001420
                                                                        001430
                                                                        001440
```
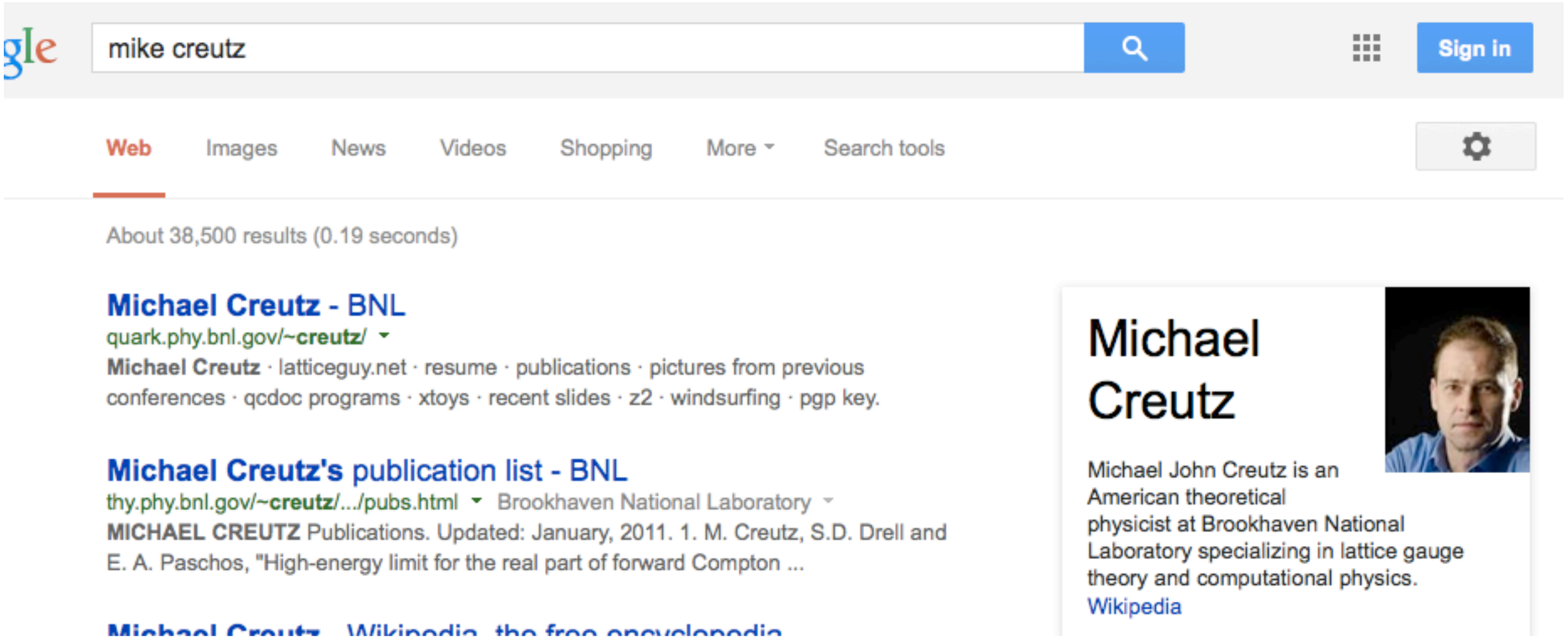

Use variable names that mean something. K&P

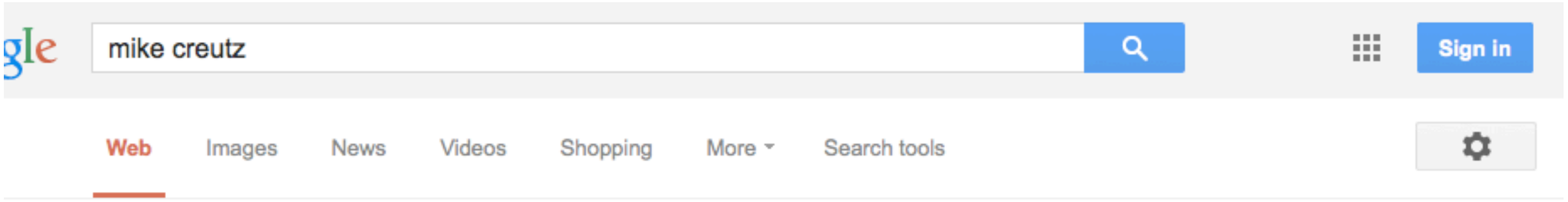
Lots of other examples...

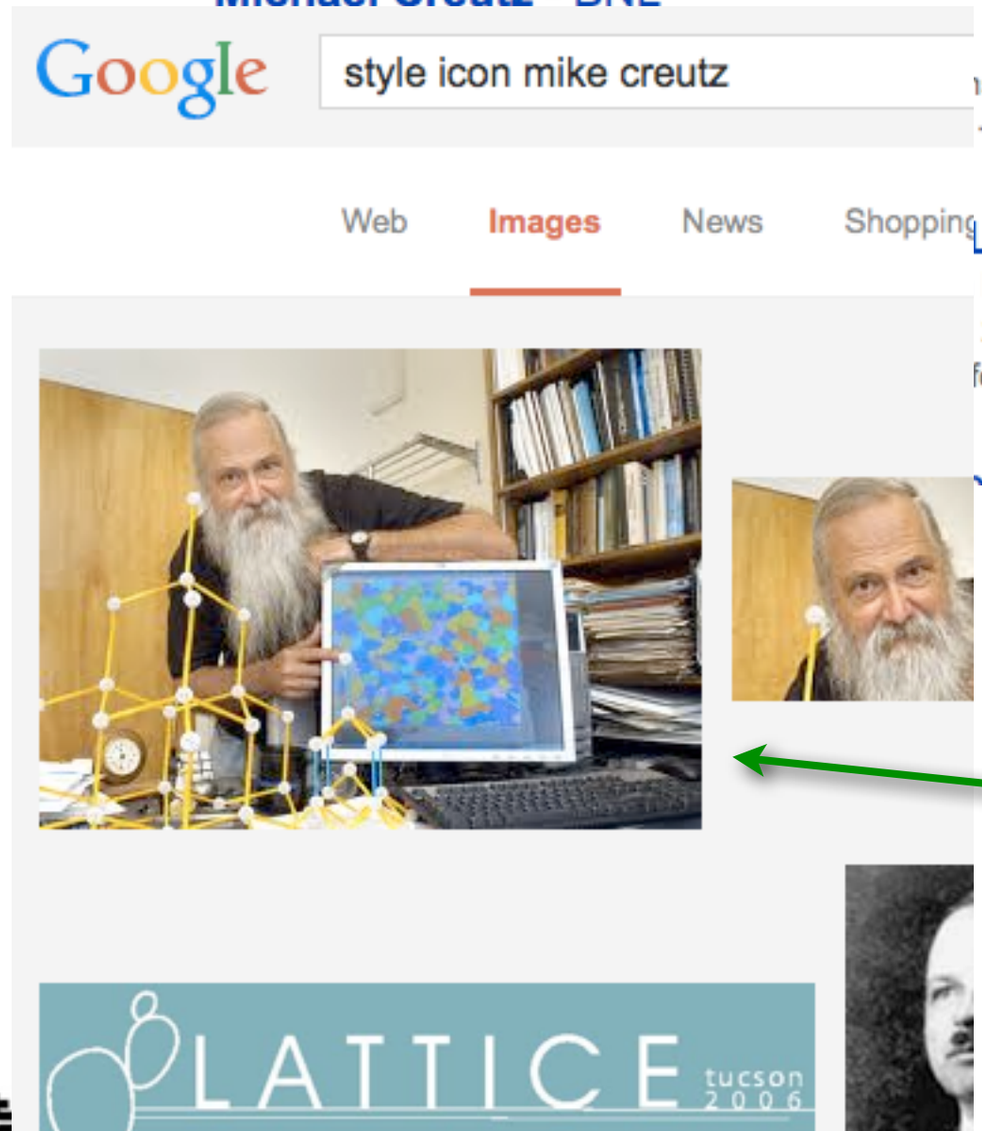
Mike Creutz: *style icon!*

Google search for Mike Creutz



Google search for Mike Creutz

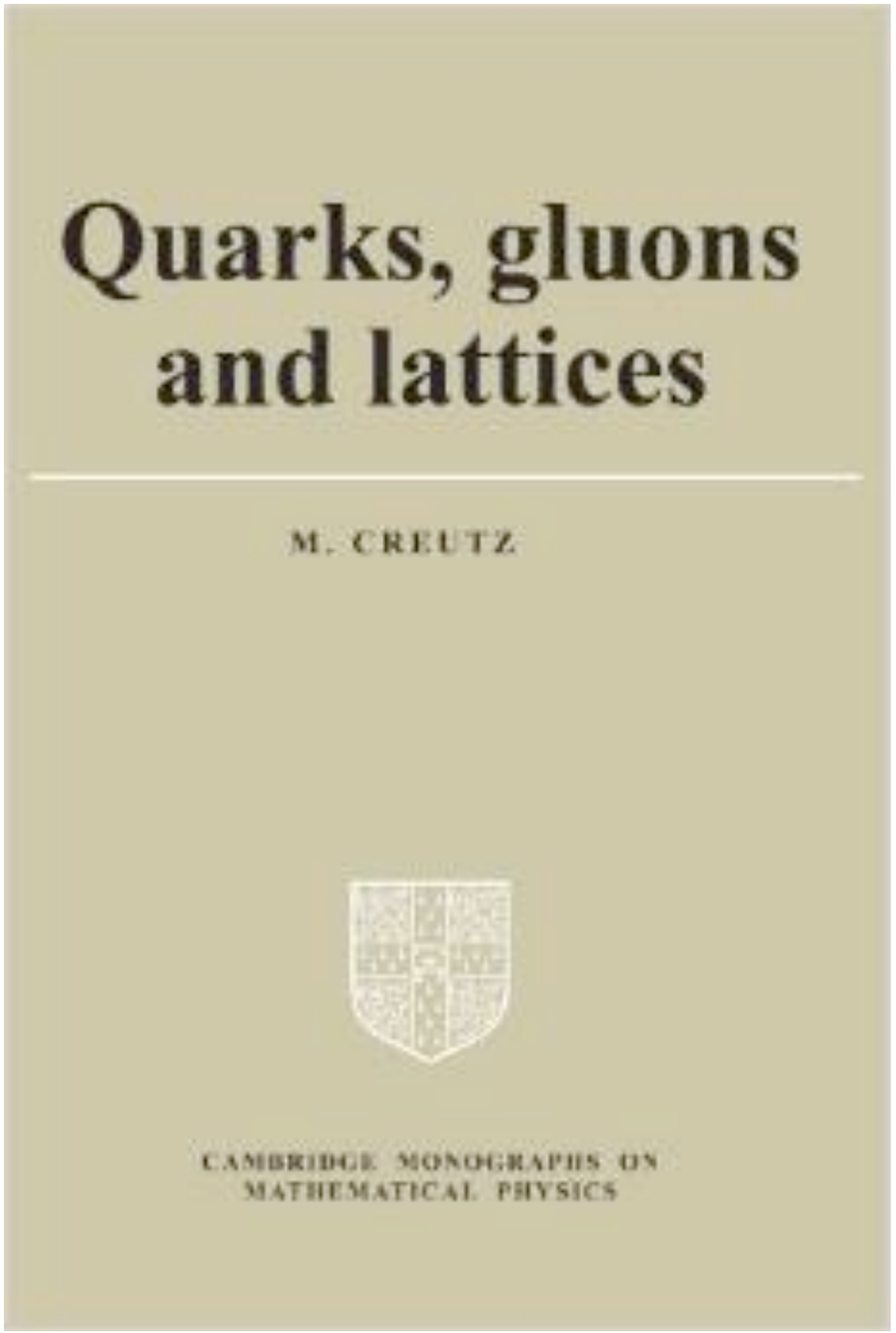




Google search web for “Mike Creutz”: wrong picture.

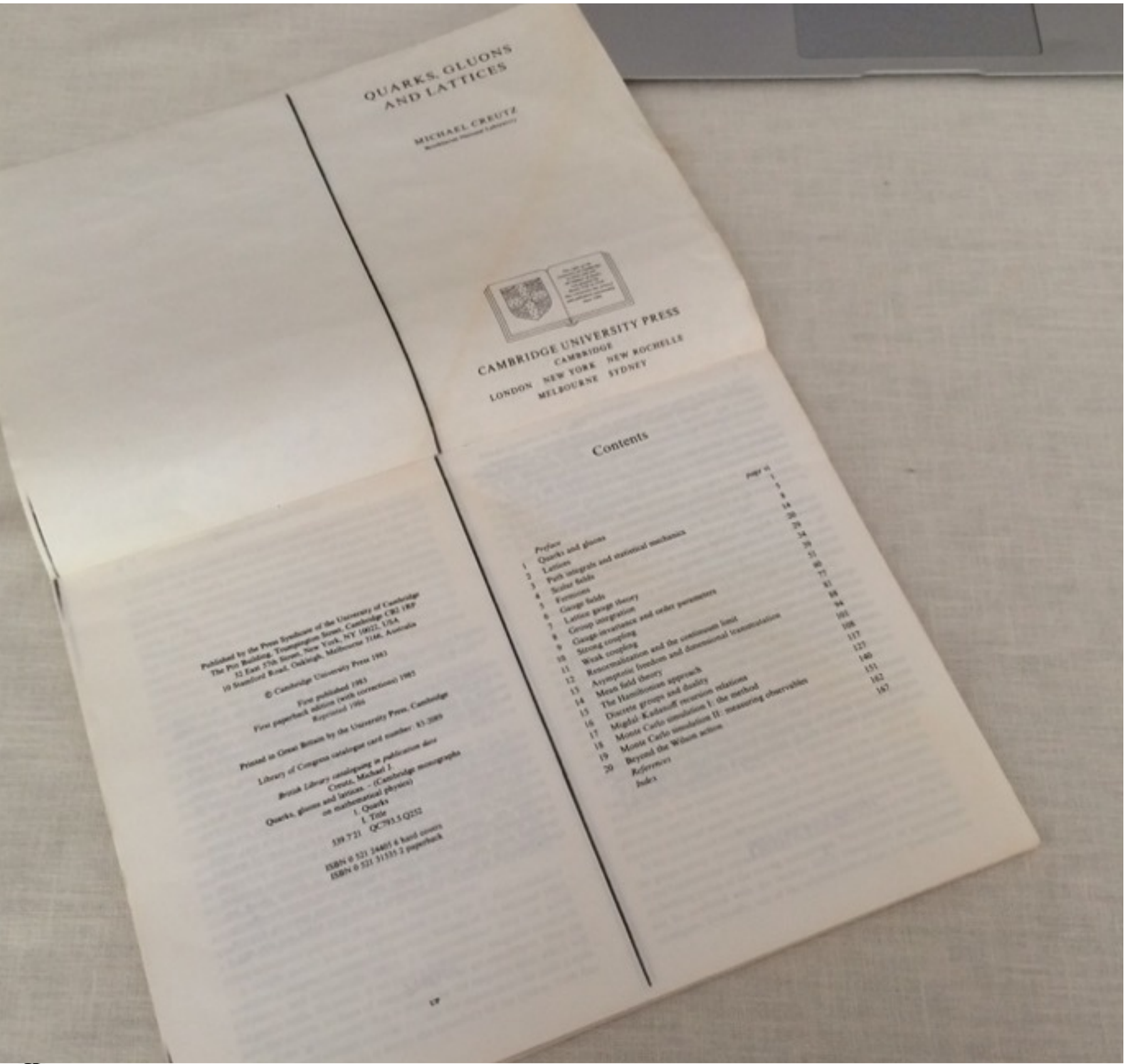
Google search images for “style icon Mike Creutz”: right picture.

Quarks, gluons, and lattices

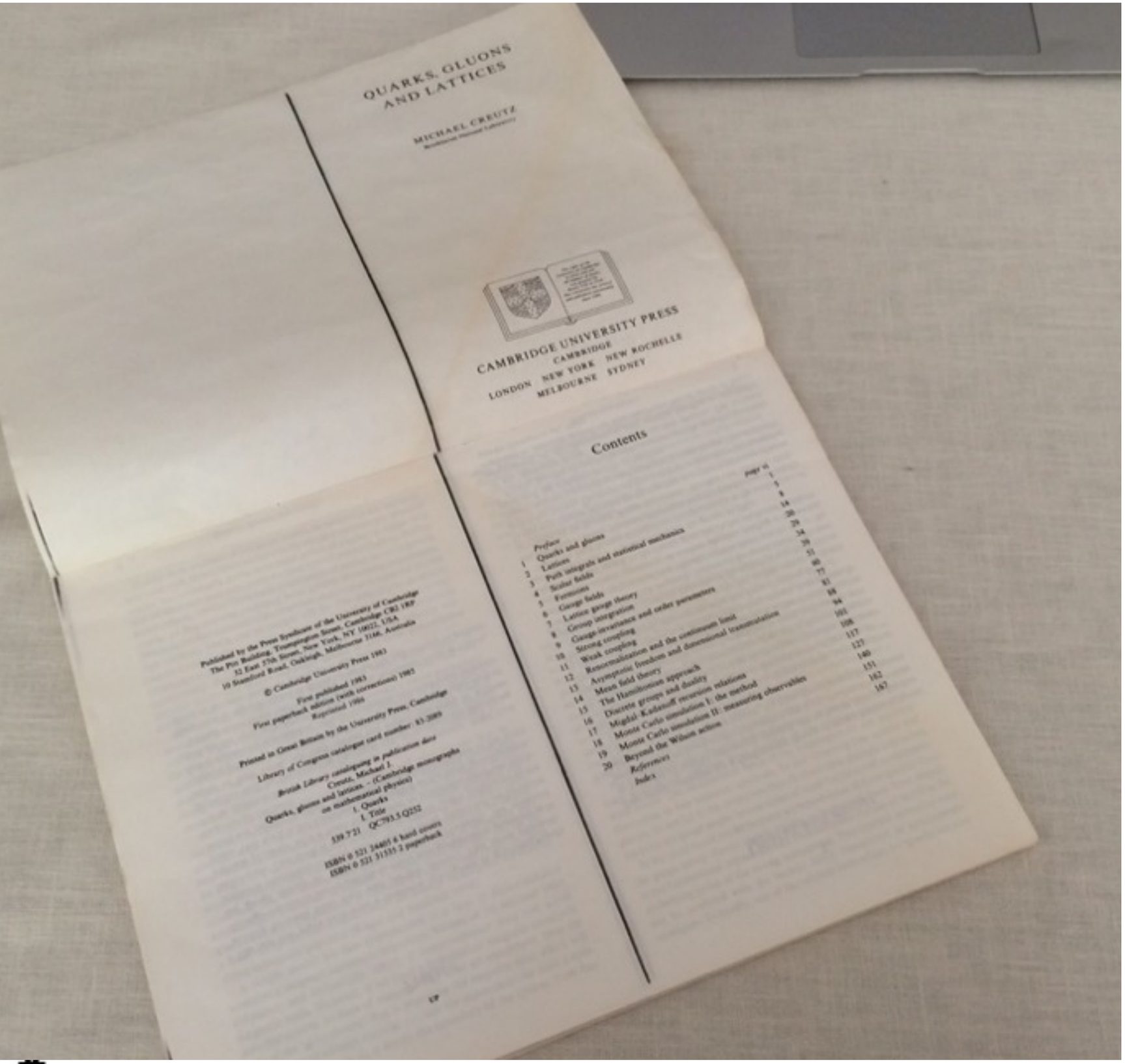


- Another important contribution of Mike's to novice lattice gauge theorists: *Quarks, gluons, and lattices.*
- Like the SU(2) program, a model of brevity and clarity.
- Important as a textbook and a reference book.

Quarks, gluons, and lattices



Quarks, gluons, and lattices

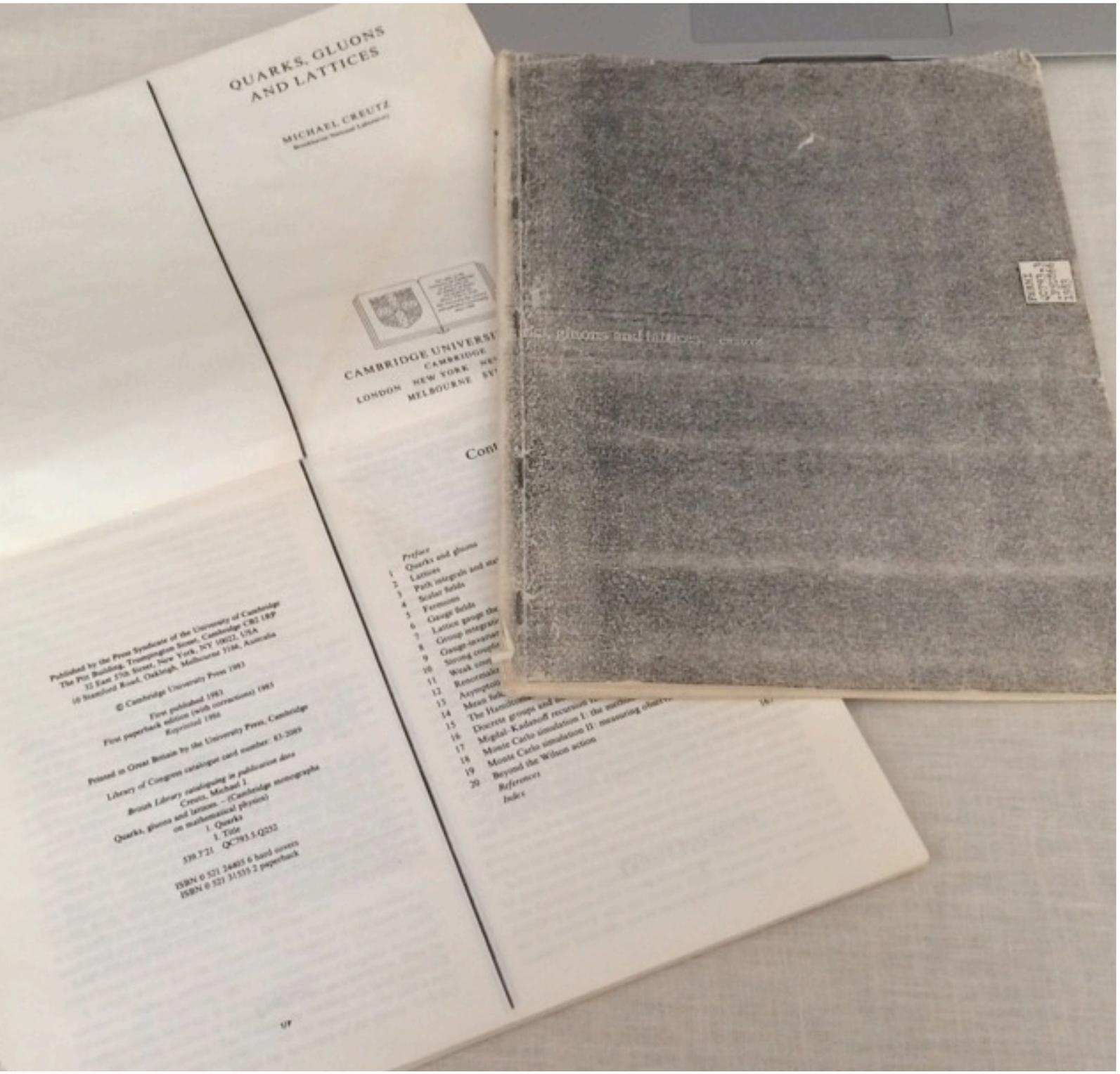


Five years ago in Mainz, bought Mike a beer to say thank you.

Quarks, gluons, and lattices

- Recent research: CUP monograph authors receive 10-15% of list price in royalties.
  - (10-15% x $54.15 = $5.41-$8.12)
  - Beer: 3 euros x 1.3 = $3.90
- Royalty deficit: $5.41-$8.12 - 3.90 = $1.51-$4.22.
  - Beer deficit: 1-2.

Quarks, gluons, and lattices



- 2x(10-15% x $54.15) = 2x($5.41-$8.12) = $10.82-$16.24
- Royalty deficit: 2x($5.41-$8.12) - 3.90 = $6.92-$12.34
- Beer deficit: 2-4

Conclusion???
We are all indebted to Mike.

We are all very indebted to Mike.

for his foundational work in the present approach to lattice QCD, and much else.

- (I in more ways than most people.)
- For your discoveries, your teaching, and your inspiration,

Thank you, Mike!