General Description

The MAX9949/MAX9950 dual parametric measurement units (PMUs) feature a small package size, wide force and measurement range, and high accuracy, making the devices ideal for automatic test equipment (ATE) and other instrumentation that requires a PMU per pin or per site.

The MAX9949/MAX9950 force or measure voltages in the -2V to +7V through -7V to +13V ranges, dependent upon the supply voltage (V_{CC} and V_{EE}). The devices handle supply voltages of up to +30V (V_{CC} to V_{EE}) and a 20V device under test (DUT) voltage swing at full current. The MAX9949/MAX9950 also force or measure currents up to ±25mA with a lowest full-scale range of ±2 μ A. Integrated support circuitry facilitates use of an external buffer amplifier for current ranges greater than ±25mA.

A voltage proportional to the measured output voltage or current is provided at the MSR_ output. Integrated comparators, with externally set voltage thresholds, provide detection for both voltage and current levels. The MSR_ and comparator outputs can be placed in a high-Z state. Integrated voltage clamps limit the force output to levels set externally. The force-current or the measure-current voltage can be offset -0.2V to +4.4V (IOS). This feature allows for the centering of the control or measured signal within the external DAC or ADC range.

The MAX9949D/MAX9950D feature an integrated $10k\Omega$ force-sense resistor between FORCE_ and SENSE_. The MAX9949F/MAX9950F have no internal force-sense resistor. These devices are available in a 64-pin 10mm x 10mm, 0.5mm pitch TQFP package with an exposed 8mm x 8mm die pad on the top (MAX9949) or the bottom (MAX9950) of the package for efficient heat removal. The exposed paddle is internally connected to VEE. The MAX9949/MAX9950 are specified over the commercial (0°C to +70°C) temperature range.

Applications

Memory Testers VLSI Testers System-on-a-Chip Testers Structural Testers

Pin Configurations appear at end of data sheet.

Features

Force Voltage/Measure Current (FVMI)

- Force Current/Measure Voltage (FIMV)
- Force Voltage/Measure Voltage (FVMV)
- Force Current/Measure Current (FIMI)
- Force Nothing/Measure Voltage (FNMV)
- ♦ Five Programmable Current Ranges ±2µA ±20µA ±200µA ±2mA ±2mA
- -2V to +7V Through -7V to +13V Input Voltage Range and Higher (Up to 20V Voltage Swing at Full Current)
- Force-Current/Measure-Current Voltage Offset (IOS)
- Programmable Voltage Clamps for the Force Output
- ♦ Low-Leakage, High-Z Measure State
- ♦ 3-Wire Serial Interface
- Low Power, 8mA (max) per PMU

Ordering Information

PART	TEMP RANGE	PIN-PACKAGE
MAX9949DCCB+	0°C to +70°C	64 TQFP-EPR*
MAX9949FCCB+	0°C to +70°C	64 TQFP-EPR*
MAX9950DCCB+	0°C to +70°C	64 TQFP-EP**
MAX9950FCCB+	0°C to +70°C	64 TQFP-EP**

+Denotes a lead(Pb)-free/RoHs-compliant part.

*EPR = Exposed pad on top.

**EP = Exposed pad on bottom.

Note: Exposed pad is internally connected to V_{EE}.

Selector Guide

PART	DESCRIPTION
MAX9949DCCB+	Internal 10k Ω force-sense resistor
MAX9949FCCB+	No internal force-sense resistor
MAX9950DCCB+	Internal 10k Ω force-sense resistor
MAX9950FCCB+	No internal force-sense resistor

_ Maxim Integrated Products 1

For pricing, delivery, and ordering information, please contact Maxim Direct at 1-888-629-4642, or visit Maxim's website at www.maxim-ic.com.

ABSOLUTE MAXIMUM RATINGS

V _{CC} to AGND	+20V
VEE to AGND	15V
V _{CC} to V _{EE}	+32V
V _L to AGND	+6V
AGND to DGND	0.5V to +0.5V
All Other Pins	$\dots (V_{EE} - 0.3V)$ to $(V_{CC} + 0.3V)$
Digital Inputs/Outputs0.3V to	o (V _L + 0.3V)Continuous Power
Dissipation ($T_A = +70^{\circ}C$)	

64-Pin TQFP-EP (derate 43.5mW/°C above +70°C)....3478mW

θ _{JA} (Note 1)	+23.0°C/W
θ _{JC} (Note 1)	+8°C/W
Junction Temperature	
Storage Temperature Range	65°C to +150°C
Operating Temperature (commercial) Range	0°C to +70°C
Lead Temperature (soldering, 10s)	+300°C
Soldering Temperature (reflow)	

Note 1: Package thermal resistances were obtained using the method described in JEDEC specification JESD51-7, using a fourlayer board. For detailed information on package thermal considerations, refer to <u>www.maxim-ic.com/thermal-tutorial</u>.

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

DC ELECTRICAL CHARACTERISTICS

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS		MIN	ТҮР	МАХ	UNITS	
FORCE VOLTAGE (Note 3)								
Force Input Voltage Range	V _{INO_,} VIN1_				V _{EE} + 3.5V		V _{CC} - 3.5V	V
		DUT current at	$V_{CC} = +12V$, V _{EE} = -7V	-2		+7	
Forced Voltage	VDUT	full scale	$V_{CC} = +18V$, V _{EE} = -12V	-7		+13	V
Toroca Voltage	201	DUT current = 0A	Ą		V _{EE} + 3.5V		V _{CC} - 3.5V	v
Input Bias Current						±1		μA
Forced-Voltage Offset Error	VFOS	$T_A = +25^{\circ}C$			-25		+25	mV
Forced-Voltage Offset Temperature Coefficient						±100		µV/°C
Forced-Voltage Gain Error	VFGE	$T_A = +25^{\circ}C$, nor	ninal gain of +	1	-1	0.005	+1	%
Forced-Voltage Gain Temperature Coefficient						±10		ppm/°C
Forced-Voltage Linearity Error	VFLER	$T_A = +25^{\circ}C$, gain and offset errors calibrated out (Notes 4, 5)		-0.02		+0.02	%FSR	
MEASURE CURRENT (Note 3)								
Measure-Current Offset	IMOS	$T_A = +25^{\circ}C$ (Note	e 4)		-1		+1	%FSR
Measure-Current Offset Temperature Coefficient						±20		ppm/°C
Measure-Current Gain Error	IMGE	$T_A = +25^{\circ}C$ (Note	e 7)		-1		+1	%
Measure-Current Gain Temperature Coefficient						±20		ppm/°C
		$T_A = +25^{\circ}C$, gair		Ranges A–D	-0.02		+0.02	%FSR
Linearity Error	IMLER	common-mode e calibrated out (N		Range E	-1		+1	nA
Measure Output Voltage Range	VALOD	VIOS = VDUTGND		·	-4		+4	V
over Full Current Range (Note 8)	VMSR	$V_{IOS} = 4V + V_{DU}$	$V_{\rm IOS} = 4V + V_{\rm DUTGND}$		0		8	v

DC ELECTRICAL CHARACTERISTICS (continued)

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS		MIN	ТҮР	MAX	UNITS
Current-Sense Amp Offset Voltage Input	V _{IOS}	Relative to V _{DUTGND}		-0.2		+4.4	V
Rejection of Output Measure Error Due to Common-Mode Sense Voltage	CMVRLER	Specified as the percent of full change at the measure output change in the DUT voltage			0.001	0.007	%FSR/V
		Range E, R_E = $1M\Omega$		-2		+2	
		Range D, R_D = $100k\Omega$		-20		+20	μA
Measure Current Range		Range C, R_C = $10k\Omega$		-200		+200	
		Range B, R_B = $1k\Omega$		-2		+2	mA
		Range A, R_A = 80Ω		-25		+25	ША
FORCE CURRENT (Note 3)	-						
Input Voltage Range for Setting	VINI	VIOS = VDUTGND		-4		+4	v
Forced Current Over Full Range	V IINI	VIOS = 4V + VDUTGND		0		+8	v
Current-Sense Amp Offset Voltage Input	VIOS	Relative to VDUTGND		-0.2		+4.4	V
V _{IOS} Input Bias Current					±1		μA
Forced-Current Offset	IFOS	$T_A = +25^{\circ}C$ (Note 4)		-1		+1	%FSR
Forced-Current Offset Temperature Coefficient					±20		ppm/°C
Forced-Current Gain Error	IFGE	$T_{A} = +25^{\circ}C$ (Note 7)		-1		+1	%
Forced-Current Gain Temperature Coefficient					±20		ppm/°C
Forced-Current Linearity Error	I _{FLER}	$T_A = +25^{\circ}C$, gain, offset, and common-mode errors	Ranges A–D	-0.02		+0.02	%FSR
	"LEN	calibrated out (Notes 4, 5, 6)	Range E	-1		+1	nA
Rejection of Output Error Due to Common-Mode Load Voltage	CMRIOER	Specified as the percent of full change of the forced current p change in the DUT voltage			+0.001	+0.007	%FSR/V
		Range E, R_E = $1M\Omega$		-2		+2	
		Range D, R_D = $100k\Omega$		-20		+20	μA
Forced-Current Range		Range C, R_C = $10k\Omega$		-200		+200	
		Range B, R_B = $1k\Omega$		-2		+2	
		Range A, R_A = 80Ω		-25		+25	mA
MEASURE VOLTAGE (Note 3)		·					
Measure-Voltage Offset	V _{MOS}	$T_A = +25^{\circ}C$		-25		+25	mV
Measure-Voltage Offset Temperature Coefficient					±100		µV/°C
Gain Error	VMGER	$T_A = +25^{\circ}C$, nominal gain of +	1	-1	±0.005	+1	%
Measure-Voltage Gain Temperature Coefficient		, , , , , , , , , , , , , , , , , , ,			±10		ppm/°C



DC ELECTRICAL CHARACTERISTICS (continued)

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	0	CONDITIONS	MIN	TYP	MAX	UNITS
Measure-Voltage Linearity Error	sure-Voltage Linearity Error V_{MLER} $T_A = +25^{\circ}C$, gain and offset errors calibrated out (Notes 4, 5, 6)		-0.02		+0.02	%FSR	
		DUT current at	$V_{CC} = +12V, V_{EE} = -7V$	-2		+7	
Measure Output Voltage Range	1/1.100	full scale	$V_{CC} = +18V, V_{EE} = -12V$	-7		+13	V
over Full DUT Voltage (V _{DUT})	VMSR	DUT current = 0	A	V _{EE} + 3.5V		V _{CC} - 3.5V	V
FORCE OUTPUT	•			•			
Off-State Leakage Current		$T_A = +25^{\circ}C$		-5		+5	nA
Chart Circuit Courset Limit	I _{LIM-}			-45		-28	
Short-Circuit Current Limit	I _{LIM+}			+28		+45	mA
Force-to-Sense Resistor	R _{FS}	D option only		7.8	10	13.3	kΩ
SENSE INPUT							
Input Voltage Range				V _{EE} + 3.5V		V _{CC} - 3.5V	V
Leakage Current				-5		+5	nA
COMPARATOR INPUTS							
Input Voltage Range				V _{EE} + 3.5V		V _{CC} - 3.5V	V
Offset Voltage		T _A = +25°C		-25		+25	mV
Input Bias Current					±1		μA
VOLTAGE CLAMPS							
Input Control Voltage	V _{CLLO} , V _{CLHI}			V _{EE} + 3.4V		V _{CC} - 3.4V	V
Clamp Voltage Range				V _{EE} + 3.5V		V _{CC} - 3.5V	V
Clamp Voltage Accuracy				-100		+100	mV
DIGITAL INPUTS							
		5V logic		+3.5			
Input High Voltage (Note 9)	VIH	3.3V logic		+2.0			V
		2.7V logic		+1.7			
		5V and 3.3V log	ic			+0.8	
Input Low Voltage (Note 9)	VIL	2.5V logic				+0.7	V
Input Current	lin				±1		μA
Input Capacitance	CIN				3.0		pF
COMPARATOR OUTPUTS (Note		•					
Output High Voltage	VOH	$V_{L} = +2.375V$ to	+5.5V, R _{PUP} = 1k Ω	V _L - 0.2			V
Output Low Voltage	Vol		+5.5V, R _{PUP} = $1k\Omega$			+0.4	V
High-Z State Leakage Current					±1		μA
High-Z State Output Capacitance					6.0		pF

DC ELECTRICAL CHARACTERISTICS (continued)

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS	MIN	ТҮР	MAX	UNITS
DIGITAL OUTPUTS (Note 9)		•				
Output High Voltage	V _{OH}	$I_{OUT} = 1$ mA, $V_L = +2.375$ V to +5.5V, relative to DGND	V _L - 0.25			V
Output Low Voltage	V _{OL}	I_{OUT} = -1mA, V _L = +2.375V to +5.5V, relative to DGND			0.2	V
POWER SUPPLY	•	•				•
Positive Supply	Vcc	(Note 2)	+10	+12	+18	V
Negative Supply	VEE	(Note 2)	-15	-7	-5	V
Total Supply Voltage	V _{CC} - V _{EE}				+30	V
Logic Supply	VL		+2.375		+5.5	V
Positive Supply Current	ICC	No load, clamps enabled			16.0	mA
Negative Supply Current	IEE	No load, clamps enabled			16.0	mA
Logic Supply Current	١L	No load, all digital inputs at rails			1.2	mA
Analog Ground Current	IAGND	No load, clamps enabled			0.9	mA
Digital Ground Current	IDGND	No load, all digital inputs at rails			1.4	mA
Power-Supply Rejection Ratio	DODD	1MHz, measured at force output		20		dD
	PSRR	60Hz, measured at force output		85		dB

AC ELECTRICAL CHARACTERISTICS

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, C_{CM} = 120pF, C_L = 100pF, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS	MIN	ТҮР	MAX	UNITS
FORCE VOLTAGE (Notes 10, 11)						
		Range E, R_E = $1M\Omega$		160		
		Range D, R_D = 100k Ω		35		
Settling Time		Range C, R_C = $10k\Omega$		25	30	μs
		Range B, R_B = $1k\Omega$		20		
		Range A, R_A = 80Ω		25		
Maximum Stable Load Capacitance			2500			pF
FORCE VOLTAGE/MEASURE CU	RRENT (Not	es 10, 11)				
		Range E, R_E = $1M\Omega$		480		
		Range D, R_D = $100k\Omega$		50]
Settling Time		Range C, R_C = $10k\Omega$		35	45	μs
		Range B, R_B = $1k\Omega$		20		
		Range A, R_A = 80Ω		25		
Range Change Switching		In addition to force-voltage and measure- current settling times, range A to range B, $R_A = 80\Omega$, $R_B = 1k\Omega$		10		μs



AC ELECTRICAL CHARACTERISTICS (continued)

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, C_{CM} = 120pF, C_L = 100pF, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS	MIN	ТҮР	MAX	UNITS
FORCE CURRENT (Notes 10, 11)		· · · · · · · · · · · · · · · · · · ·				
		Range E, R_E = $1M\Omega$		300		
		Range D, R_D = $100k\Omega$		100		
Settling Time		Range C, R_C = $10k\Omega$		40	45	μs
		Range B, R_B = $1k\Omega$		25		
		Range A, R_A = 80Ω		25		
FORCE CURRENT/MEASURE VO	LTAGE (Not	es 10, 11, 12)				
		Range E, R_E = $1M\Omega$		1600		
		Range D, R_D = $100k\Omega$		170		
Settling Time		Range C, R_C = $10k\Omega$		40	50	μs
		Range B, R_B = $1k\Omega$		25		
		Range A, R_A = 80Ω		25		
Range Change Switching		In addition to force-voltage and measure- current settling times, range A to range B, $R_A = 80\Omega$, $R_B = 1k\Omega$		12		μs
SENSE INPUT TO MEASURE OU	TPUT PATH	(Note 12)				
Settling Time		C _{LMSR} = 100pF		0.2		μs
MEASURE OUTPUT						
HIZ_ or HIZMSR True (0) to High-Z		C _{LMSR} = 100pF, measured from 50% of digital input voltage to 10% of output voltage		250		ns
HIZ_ or HIZMSR False (1) to Active		C _{LMSR} = 100pF, measured from 50% of digital input voltage to 90% of output voltage		5		μs
Maximum Stable Load Capacitance			1000			pF
FORCE OUTPUT		· · · · · · · · · · · · · · · · · · ·				
HIZFORCE True (0) to High-Z		Measured from 50% of digital input voltage to 10% of output voltage		2		μs
HIZFORCE False (1) to Active		Measured from 50% of digital input voltage to 90% of output voltage		2		μs
COMPARATORS						
Propagation Delay		50mV overdrive, $1V_{P-P}$, $C_{LCOMP} = 20pF$, $R_{PUP} = 1k\Omega$ measured from input-threshold zero crossing to 50% of output voltage (Note 13)		75		ns
Rise Time		C_{LCOMP} = 20pF, R_{PUP} = 1k Ω measured from input-threshold zero crossing to 50% of output voltage		60		ns
Fall Time		$C_{LCOMP} = 20pF, R_{PUP} = 1k\Omega, 20\%$ to 80%		5		ns

AC ELECTRICAL CHARACTERISTICS (continued)

 $(V_{CC} = +12V, V_{EE} = -7V, V_L = +3.3V, C_{CM} = 120pF, C_L = 100pF, T_A = T_{MIN}$ to T_{MAX} , unless otherwise noted. $T_A < +25^{\circ}C$ guaranteed by design and characterization. Typical values are at $T_A = +25^{\circ}C$, unless otherwise specified.) (Note 2)

PARAMETER	SYMBOL	CONDITIONS	MIN	ТҮР	МАХ	UNITS
DISABLE True (0) to High-Z		C _{LCOMP} = 20pF, measured from 50% of digital input voltage to 10% of output voltage		300		ns
DISABLE False (1) to Active		C _{LCOMP} = 20pF, measured from 50% of digital input voltage to 90% of output voltage		100		ns
SERIAL PORT (VL = +3.0V, CDOU	т = 10рF)					
Serial Clock Frequency	f SCLK				20	MHz
SCLK Pulse-Width High	tсн		12			ns
SCLK Pulse-Width Low	tCL		12			ns
SCLK Fall to DOUT Valid	tdo				22	ns
CS Low to SCLK High Setup	tcsso		10			ns
SCLK High to \overline{CS} High Hold	tCSH1		22			ns
SCLK High to \overline{CS} Low Hold	tCSH0		0			ns
CS High to SCLK High Setup	tCSS1		5			ns
DIN to SCLK High Setup	tDS		10			ns
DIN to SCLK High Hold	tDH	(Note 14)	0			ns
CS Pulse-Width High	tcswh		10			ns
CS Pulse-Width Low	tcswl		10			ns
LOAD Pulse-Width Low	tldw		20			ns
V_{DD} High to \overline{CS} Low (Power-Up)		(Note 14)			500	μs

Note 2: The device operates properly with different supply voltages with equally different voltage swings.

Note 3: Tested at $V_{CC} = +18V$ and $V_{EE} = -12V$.

Note 4: Interpret errors expressed in terms of %FSR (percent of full-scale range) as a percentage of the end-point to end-point range, i.e., for the ±25mA range, the full-scale range = 50mA and a 1% error = 500µA.

Note 5: Case must be maintained ±5°C for linearity specifications.

Note 6: Current linearity specifications are maintained to within 700mV of the clamp voltages when the clamps are enabled.

Note 7: Tested in range C.

Note 8: Linearity of the measured output is only guaranteed within the specified current range.

Note 9: The digital interface accepts +5V, +3.3V, and +2.5V CMOS logic levels. The voltage at VL adjusts the threshold.

Note 10: Settling times are to 0.1% of FSR. Cx = 47pF.

Note 11: All settling times are specified using a single compensation capacitor (Cx) across all current-sense resistors. Use an individual capacitor across each sense resistor for better performance across all current ranges, particularly the lower ranges.

Note 12: The actual settling time of the measured voltage path (SENSE_ input to MSR_ output) is less than 1µs. However, the R-C time constant of the sense resistor and the load capacitance causes a longer overall settling time of the DUT voltage. This settling time is a function of the current-range resistor used.

Note 13: The propagation delay time is only guaranteed over the force-voltage output range. Propagation delay is measured by holding the SENSE_ input voltage steady and transitioning THMAX_ or THMIN_.

Note 14: Guaranteed by design.

10kΩ, R_L = 22.5kΩ; range D: R_D = 100kΩ, R_L = 225kΩ; range E: R_E = 1MΩ, R_L = 2.25MΩ, T_A = +25°C.

 $(V_{CC} = +12V, V_{EE} = -7V, C_{L} = 100pF, R_{L}$ to +2.5V, range A: R_A = 80 Ω , R_L = 180 Ω ; range B: R_B = 1k Ω , R_L = 2.25k Ω ; range C: R_C =



TRANSIENT RESPONSE FIMI MODE **RANGE E**











Typical Operating Characteristics

__Pin Description

PIN						
MAX9950	MAX9949	NAME	FUNCTION			
1, 16, 33, 48	1, 16, 33, 48	V _{EE}	Negative Analog Supply Input			
2, 15, 34, 47	2, 15, 34, 47	V _{CC}	Positive Analog Supply Input			
3	14	RBCOM	PMU-B Range-Setting-Resistor Common Connection. Connect to one end of all the range- setting resistors (RB_) for PMU-B. Also serves as the input to an external current-range buffer for PMU-B.			
4	13	RBE	PMU-B Range E Resistor Connection			
5	12	RBD	PMU-B Range D Resistor Connection			
6	11	RBC	PMU-B Range C Resistor Connection			
7	10	RBB	PMU-B Range B Resistor Connection			
8	9	RBA	PMU-B Range A Resistor Connection			
9	8	FORCEB	PMU-B Driver Output. Forces a current or voltage to the DUT for PMU-B.			
10	7	SENSEB	PMU-B Sense Input. A Kelvin connection to the DUT. Provides the feedback signal in FVMI mode and the measured signal in FIMV mode for PMU-B.			
11	6	CC1B	PMU-B Compensation Capacitor Connection 1. Provides compensation for the PMU-B main amplifier.			
12	5	CC2B	PMU-B Compensation Capacitor Connection 2. Provides compensation for the PMU-B main amplifier.			
13	4	RXDB	PMU-B Current-Range Sense-Resistor Connection. Connects to the external current-range sense resistor on the DUT side for PMU-B. See Figure 5.			
14	3	RXAB	PMU-B Current-Range Sense-Resistor Connection. Connects to the external current-range sense resistor on the amplifier side for PMU-B. See Figure 5.			
17	64	CS	Chip-Select Input. Force \overline{CS} low to enable communication with the serial port.			
18	63	LOAD	Serial Port Load Input. A logic low asynchronously loads data from the input registers into the PMU registers.			
19	62	SCLK	Serial Clock Input			
20	61	DIN	Serial Data Input			
21	60	DUTHB	PMU-B Window-Comparator High-Comparator Output. A sense-B voltage above the V _{THMAXB} level forces the DUTHB output low. DUTHB is an open-drain output.			
22	59	DUTLB	PMU-B Window-Comparator Low-Comparator Output. A sense-B voltage below the V _{THMINB} level forces the DUTLB output low. DUTLB is an open-drain output.			
23	58	EXTBSEL	PMU-B External Current-Range Selector. Selects the external current range for PMU-B.			
24, 27	54, 57	DGND	Digital Ground			
25	56	DOUT	Serial Data Output. Provides data out from the shift register. Facilitates daisy-chaining to DIN of a downstream PMU.			
26	55	VL	Logic Supply Voltage Input. The voltage applied at VL sets the upper logic-voltage level.			
28	53	EXTASEL	PMU-A External Current-Range Selector. Selects the external current range for PMU-A.			
29	52	DUTLA	PMU-A Window-Comparator Low-Comparator Output. A sense-A voltage below the V _{THMINA} level forces the DUTLA output low. DUTLA is an open-drain output.			

_____Pin Description (continued)

PIN			FUNCTION		
MAX9950	MAX9949	NAME	FUNCTION		
30	51	DUTHA	PMU-A Window-Comparator High-Comparator Output. A sense-A voltage above the V _{THMAXA} level forces the DUTHA output low. DUTHA is an open-drain output.		
31	50	HI-ZB	PMU-B MSRB Output State Control. A logic low places the MSRB output in a high-impeda state.		
32	49	HI-ZA	PMU-A MSRA Output State Control. A logic low places the MSRA output in a high-impedance state.		
35	46	RXAA	PMU-A Current-Range Sense-Resistor Connection. Connects to the external current-range sense resistor on the amplifier side for PMU-A. See Figure 5.		
36	45	RXDA	PMU-A Current-Range Sense-Resistor Connection. Connects to the external current-range sense resistor on the DUT side for PMU-A. See Figure 5.		
37	44	CC2A	PMU-A Compensation Capacitor Connection 2. Provides compensation for the PMU-A main amplifier.		
38	43	CC1A	PMU-A Compensation Capacitor Connection 1. Provides compensation for the PMU-A main amplifier.		
39	42	SENSEA	PMU-A Sense Input. A Kelvin connection to the DUT. Provides the feedback signal in FVMI mode and the measured signal in FIMV mode for PMU-A.		
40	41	FORCEA	PMU-A Driver Output. Forces a current or voltage to the DUT for PMU-A.		
41	40	RAA	PMU-A Range A Resistor Connection		
42	39	RAB	PMU-A Range B Resistor Connection		
43	38	RAC	PMU-A Range C Resistor Connection		
44	37	RAD	PMU-A Range D Resistor Connection		
45	36	RAE	PMU-A Range E Resistor Connection		
46	35	RACOM	PMU-A Range-Setting-Resistor Common Connection. Connect to one end of all range-setting resistors (RA_) for PMU-A. Also serves as the input to an external current range buffer for PMU-A.		
49	32	THMAXA	PMU-A Window-Comparator Upper Threshold Voltage Input. Sets the upper voltage threshold for the PMU-A window comparator.		
50	31	THMINA	PMU-A Window-Comparator Lower Threshold Voltage Input. Sets the lower voltage threshold for the PMU-A window comparator.		
51	30	CLHIA	PMU-A Upper Clamp Voltage Input. Sets the upper clamp voltage level for PMU-A.		
52	29	CLLOA	PMU-A Lower Clamp Voltage Input. Sets the lower clamp voltage level for PMU-A.		
53	28	INOA	Input Voltage 0 for PMU-A. Sets the forced current in FI mode or the forced voltage in FV mode for PMU-A.		
54	27	IN1A	Input Voltage 1 for PMU-A. Sets the forced voltage in FV mode or the forced current in FI mode for PMU-A.		
55	26	MSRA	PMU-A Measurement Output. Provides a voltage equal to the SENSE voltage in FIMV mode and provides a voltage proportional to the DUT current in FVMI mode for PMU-A. Force HI-ZA low to place MSRA in a high-impedance state.		
56	25	IOS	Offset Voltage Input. Sets an offset voltage for the internal current-sense amplifier for both PMU-A and -B.		
57	24	AGND	Analog Ground		

Pin Description (continued)

P	PIN		FUNCTION	
MAX9950	MAX9949	NAME	FUNCTION	
58	58 23 MSRB		PMU-B Measurement Output. Provides a voltage equal to the SENSE voltage in FIMV mode and provides a voltage proportional to the DUT current in FVMI mode for PMU-B. Force HI-ZB low to place MSRB in a high-impedance state.	
59	22	IN1B	Input Voltage 1 for PMU-B. Sets the forced voltage in FV mode or the forced current in FI mode for PMU-B.	
60	21	INOB	Input Voltage 0 for PMU-B. Sets the forced current in FI mode or the forced voltage in FI mode for PMU-B.	
61	20	CLLOB	PMU-B Lower-Clamp Voltage Input. Sets the lower clamp voltage level for PMU-B.	
62	19	CLHIB	PMU-B Upper-Clamp Voltage Input. Sets the upper clamp voltage level for PMU-B.	
63	18	THMINB	PMU-B Window-Comparator Lower Threshold Voltage Input. Sets the lower voltage threshold for the PMU-B window comparator.	
64	17	THMAXB	PMU-B Window-Comparator Upper Threshold Voltage Input. Sets the upper voltage threshold for the PMU-B window comparator.	
_	_	EP	Exposed Pad. Internally connected to V_{EE} . Connect to V_{EE} power plane.	

Detailed Description

The MAX9949/MAX9950 force or measure voltages in the -2V to +7V through -7V to +13V ranges, dependent upon the supply voltage range (V_{CC} and V_{EE}). However, the devices can handle supply voltages up to +30V (V_{CC} to V_{EE}) and a 20V DUT voltage swing at full current. The MAX9949/MAX9950 PMU also force or measure currents up to ±25mA, with a lowest full-scale range of ±2 μ A. Use an external buffer amplifier for current ranges greater than ±25mA.

The MSR_ output presents a voltage proportional to the measured voltage or current. Place MSR_ in a low-leakage, high-impedance state by pulling HI-Z_ low. Integrated comparators with externally programmable voltage thresholds provide "too low" (DUTL_) and "too high" (DUTH_) voltage-monitoring outputs. Each comparator output features a selectable high-impedance state. The devices feature separate FORCE_ and SENSE_ connections and are fully protected against short circuits. The FORCE_ output has two voltage clamps, negative (CLLO_) and positive (CLHI_), to limit the voltage to externally provided levels. Two control voltage inputs, selected independently of the PMU mode, allow for greater flexibility.

Serial Interface The MAX9949/MAX9950 use a standard 3-wire SPI™/QSPI™/MICROWIRE™-compatible serial port.

SPI and QSPI are trademarks of Motorola, Inc. MICROWIRE is a trademark of National Semiconductor, Corp. Once the input data register fills, the data becomes available at DOUT. This data output allows for daisy-chaining multiple devices. Figures 1, 2, and 3 show the serial interface timing diagrams.

Serial Port Speed

The serial port timing specifications are measured at a logic supply voltage (V_L) of +3.0V, ensuring operation of the serial port at rated speed for V_L from +3.0V to +5.5V.

The serial interface has two ranks. Each PMU has an input register that loads from the serial port shift register. Each PMU also has a PMU register that loads from the input register. Data does not affect the PMU until it reaches the PMU register. This register configuration permits loading of the PMU data into the input register at one time and then latching the input register data into the PMU register later, at which time the PMU function changes accordingly. The register configuration also provides the ability to change the state of the PMU asynchronously with respect to the loading of that PMU's data into the serial port. Thus, the PMU easily updates simultaneously with other PMUs or other devices.

Use the $\overline{\text{LOAD}}$ input to asynchronously load all input registers into the PMU registers. If $\overline{\text{LOAD}}$ remains low when data latches into an input register, the data also transfers to the PMU register.





Functional Diagram

Dual Per-Pin Parametric Measurement Units



Figure 1. Serial Port Timing with Asynchronous Load



Figure 2. Serial Port Timing with Synchronous Load



Figure 3. Detailed Serial Port Timing Diagram



Figure 4. Dual PMU Serial Port Block Diagram

Table 1. Bit Order

BIT	BIT NAME
15	IN _{MODE}
14	Fmode
13	MMODE
12	RS2
11	RS1
10	RSO
9	CLENABLE
8	HI-ZFORCE
7	HI-ZMSR
6	DISABLE
5	Don't care
4	Don't care
3	A2
2	A1
1	C2
0	C1

Table 2. Address Bit

A2	A1	OPERATION		
0	0	Do not update any input register (NOP).		
0	1	Only update input register A.		
1	0	Only update input register B.		
1	1	Update both input registers with the same data.		

Table 3. Control Bit

C2	C1	OPERATION		
0	0	Data stays in input register.		
0	1	Transfer PMU-A input register to PMU register.		
1	0	Transfer PMU-B input register to PMU register.		
1	1	Transfer both input registers to the PMU registers.		

PMU Control

Programming both PMUs with the same data requires a 16-bit word. Programming each PMU with separate data requires two 16-bit words.

The address bits specify which input registers the shift register loads. Table 2 describes the function of the address bits.

Bits (C2, C1) specify how the data loads into the second rank PMU registers. These two control bits serve a similar function as the $\overline{\text{LOAD}}$ input. The specified actions occur when $\overline{\text{CS}}$ goes high, whereas the $\overline{\text{LOAD}}$ input loads the PMU register anytime. When either C2 or C1 is low, the corresponding PMU register is transparent. Table 3 describes the function of the two control bits.

The NOP operation requires A1 = A2 = C1 = C2 = 0. In this case, the data transfers through the shift register without changing the state of the MAX9949/MAX9950.

C1 = C2 = 0 allows for data transfer from the shift register to the input register without transferring data to the PMU register (unless the LOAD input is low). This permits the latching of data into the PMU register at a later time by the LOAD input or subsequent command.

Table 4 summarizes the possible control and address bit combinations.

When asynchronously latching only one PMU's data, the input register of the other PMU maintains the same data. Therefore, loading both PMU registers would update the one PMU with new data while the other PMU remains in its current state.

Mode Selection

Four bits from the control word select between the various modes of operation. INMODE selects between the two input analog control voltages. FMODE selects whether the PMU forces a voltage or a current. MMODE selects whether the DUT current or DUT voltage is directed to the MSR_ output. HI-ZFORCE places the driver amplifier in a high-output impedance state. Table 5 describes the various force and measure modes of operation.

A2	A1	C2	C1	PMU-B OPERATION	PMU-A OPERATION		
0	0	0	0	NOP: data jus	NOP: data just passes through.		
0	0	0	1	NOP.	Load PMU register A from input register A.		
0	0	1	0	Load PMU register B from input register B.	NOP.		
0	0	1	1	Load PMU register B from input register B.	Load PMU register A from input register A.		
0	1	0	0	NOP.	Load input register A from shift register.		
0	1	0	1	NOP.	Load input register A and PMU register A from shift register.		
0	1	1	0	Load PMU register B from input register B.	Load input register A from shift register.		
0	1	1	1	Load PMU register B from input register B.	Load input register A and PMU register A from shift register.		
1	0	0	0	Load input register B from shift register.	NOP.		
1	0	0	1	Load input register B from shift register.	Load PMU register A from input register A.		
1	0	1	0	Load input register B and PMU register B from shift register.	NOP.		
1	0	1	1	Load input register B and PMU register B from shift register.	Load PMU register A from input register A.		
1	1	0	0	Load input register B from shift register.	Load input register A from shift register.		
1	1	0	1	Load input register B from shift register.	Load input register A and PMU register A from shift register.		
1	1	1	0	Load input register B and PMU register B from shift register.	Load input register A from shift register.		
1	1	1	1	Load input register B and PMU register B from shift register.	Load input register A and PMU register A from shift register.		

Table 4. PMU Operation Using Control and Address Bits

Table 5. PMU Force/Measure Mode Selection

IN MODE	F MODE	M MODE	HI-ZFORCE	PMU MODE	FORCE OUTPUT	MEASURE OUTPUT	ACTIVE INPUT
0	0	0	1	FVMI	Voltage	IDUT	VINO
1	0	0	1	FVMI	Voltage	IDUT	VIN1
0	0	1	1	FVMV	Voltage	Vdut	VINO
1	0	1	1	FVMV	Voltage	VDUT	VIN1
0	1	0	1	FIMI	Current	IDUT	VINO
1	1	0	1	FIMI	Current	IDUT	V _{IN1}
0	1	1	1	FIMV	Current	VDUT	VINO
1	1	1	1	FIMV	Current	Vdut	VIN1
Х	Х	0	0	FNMI—Meaningless mode			
Х	х	1	0	FNMV	HI-Z	V _{DUT}	Х



MAX9949/MAX9950

Table 6. Current Range Selection

RS2	RS1	RS0	RANGE	NOMINAL RESISTOR VALUE
0	0	0	±2µA	$R_E = 1M\Omega$
0	0	1	±2µA	$R_E = 1M\Omega$
0	1	0	±20µA	$R_D = 100 k\Omega$
0	1	1	±200µA	$R_C = 10k\Omega$
1	0	0	±2mA	$R_B = 1k\Omega$
1	0	1	±25mA	R_A = 80Ω
1	1	0	External	_
1	1	1	±25mA	R_A = 80Ω

Current-Range Selection

Three bits from the control word, RS0, RS1, RS2, control the full-scale current range for either FI (force current) or MI (measure current). Table 6 describes the full-scale current-range control.

Clamp Enable

The CL_{ENABLE} bit enables the force-output voltage clamps when high and disables the clamps when low. Table 7 depicts the various clamp mode options.

Measure Output High-Impedance Control

The MSR_ output attains a low-leakage, high-impedance state by using the HI-ZMSR control bit or the HI-Z_ input. The 2 bits are logically ORed together to control the MSR_ output. The HI-Z_ input allows external multiplexing among several PMU MSR_ outputs without using the serial interface. Table 8 explains the various output modes for the MSR_ output.

Digital Output (DOUT)

The digital output follows the last output of the serial shift register and clocks out on the falling edge of the input clock. DOUT provides the first bit of the incoming serial data word 16.5 clock cycles later. This allows for daisy-chaining an additional device using DOUT and the same clock.

Table 7. Clamp Enable

CLENABLE	MODE
1	Clamps enabled
0	Clamps disabled

Table 8. MSR_ Output Truth Table

HI-ZMSR	HĪ-Z_	MSR_ STATE
1	1	Measure output enabled
0	1	High-Z
1	0	High-Z
0	0	High-Z

"Quick Load" Using Chip Select

If CS goes low and then returns high without any clock activity, the data from the input registers latch into the PMU registers. This extra function is not standard for SPI/QSPI/MICROWIRE interfaces. The quick load mimics the function of LOAD without forcing LOAD low.

Comparators

Two comparators configured as a window comparator monitor the MSR_ output. THMAX_ and THMIN_ set the high and low thresholds that determine the window. Both outputs are open drain and share a single disable control that places the outputs in a high-Z, low-leakage state. Table 9 describes the comparator output states of the MAX9949/MAX9950.

Table 9. Comparator Truth Table

•			
DISABLE	CONDITION	DUTH_	DUTL_
0	Х	High-Z	High-Z
1	$V_{MSR} > V_{THMAX}$ and V_{THMIN}	0	1
1	VTHMAX > VMSR > VTHMIN	1	1
1	V _{THMAX} and V _{THMIN} > V _{MSR}	1	0
1	VTHMIN > VMSR > VTHMAX*	0	0

*VTHMAX > VTHMIN constitutes normal operation. This condition, however, has VTHMIN > VTHMAX and does not cause any problems with the operation of the comparators.



Applications Information

In force-voltage (FV) mode, the output FORCE_ voltage is directly proportional to the input control voltage. In force-current (FI) mode, the current flowing out of the FORCE_ output is proportional to the input control voltage. Positive current flows out of the PMU.

In force-nothing (FN) mode, the FORCE_ output is high impedance.

In measure-current (MI) mode, the voltage at the MSR_ output is directly proportional to the current exiting the FORCE_ output. Positive current flows out of the PMU.

In measure-voltage (MV) mode, the voltage at the MSR_ output is directly proportional to the voltage at the SENSE_ input.

Current-Sense-Amplifier Offset Voltage Input

IOS is a buffered input to the current-sense amplifier. The current-sense amplifier converts the input control voltage (IN0_ or IN1_) to the forced DUT current (FI) AND converts the sensed DUT current to the MSR_ output voltage (MI). When IOS equals zero relative to DUT-GND (the GND voltage at the DUT, which the level-setting DACs and the ADC are presumed to use as a ground reference), the nominal voltage range that corresponds to \pm full-scale current is -4V to +4V. Any voltage applied to the IOS input adds directly to this control input/measure output voltage range that corresponds to \pm full-scale current from 0 to +8V.



Figure 5. External Current Boost

The following equations determine the minimum and maximum currents for each current range corresponding to the input voltage or measure voltage:

Choose IOS so the limits of the MSR_ output do not go closer than 2.8V to either V_{EE} or V_{CC}. For example, with supplies of +10V and -5V, limit the MSR_ output to -2.2V and +7.2V. Therefore, set IOS between +1.8V and +3.2V. The MSR_ output could clip if IOS is not within this range. Use these general equations for the limits on IOS:

 $\label{eq:VIOS} \begin{aligned} \text{Minimum V}_{\text{IOS}} &= \text{V}_{\text{EE}} + 6.8\text{V} \\ \text{Maximum V}_{\text{IOS}} &= \text{V}_{\text{CC}} - 6.8\text{V} \end{aligned}$

Current Booster for Highest Current Range

An external buffer amplifier can be used to provide a current range greater than the MAX9949/MAX9950 maximum output current (Figure 5). This function operates as follows.

A digital output decoded from the range select bits, EXTSEL_, indicates when to activate the booster. The R_COM output serves as an input to an external buffer through a 50Ω current-limit series resistor. Each side of the external current-sense resistor feeds back to RXA_ and RXD_. Ensure that the buffer circuit enters a high-Z output state when not selected. Any leakage in the buffer adds to the leakage of the PMU.

Voltage Clamps

The voltage clamps limit the FORCE_ output and operate over the entire specified current range. Set the clamp voltages externally at CLHI_ and CLLO_. The voltage at the FORCE_ output triggers the clamps independent of the voltage at the SENSE_ input. When enabled, the clamps function in both FI and FV modes.

Current Limit

The current-limiting circuitry on the FORCE_ output ensures a well-behaved MSR_ output for currents between the full current range and the current limits, i.e., for currents greater than the full-scale current, the MSR_ voltage is greater than +4V and for currents less than the full-scale current, the MSR_ voltage is less than -4V.

Independent Control of the Feedback Switch and the Measure Switch

Two single-pole-double-throw (SPDT) switches determine the mode of operation of the PMU. One switch determines whether the sensed DUT current or DUT voltage feeds back to the input (sensing), and thus





Figure 6. Force-Voltage/Measure-Current Functional Diagram

determines whether the MAX9949/MAX9950 force current or voltage. The other switch determines whether the MSR_ output senses the DUT current or DUT voltage.

Independent control of these switches and the HI-ZFORCE state permits flexible modes of operation beyond the traditional force-voltage/measure-current (FVMI) and force-current/measure-voltage (FIMV) modes. The MAX9949/MAX9950 support the following five modes:

- FVMI
- FIMV
- FVMV
- FIMI
- FNMV

Figure 6 shows the internal path structure for force-voltage/measure-current mode. In force-voltage/measurecurrent mode, the current across the appropriate external sense resistor (R_A to R_E) provides a voltage to the MSR_ output. The SENSE_ input samples the voltage at the DUT and feeds the buffered result back to the negative input of the voltage amplifier. The voltage at MSR_ is proportional to the FORCE_ current in accordance with the following formula:

VMSR_ = IFORCE_ X RSENSE X 2

Figure 7 shows the internal path structure for the forcecurrent/measure-voltage mode. In force-current/measure-voltage mode, the appropriate external sense resistor (R_A to R_E) provides a feedback voltage to the inverting input of the voltage amplifier. The SENSE_ input samples the voltage at the DUT and provides a buffered result at the MSR_ output.



Figure 7. Force-Current/Measure-Voltage Functional Diagram

High-Z States

The FORCE_, MSR_, and comparator outputs feature individual high-Z control that places them into a high-impedance, low-leakage state. The high-Z state allows busing of MSR_ and comparator outputs with other PMU measure and comparator outputs. The FORCE_ output high-Z state allows for additional modes of operation as described in Table 5 and can eliminate the need for a series relay in some applications.

The FORCE_, MSR_, and comparator outputs power up in the high-Z state.

Input Source Selection and Gating

Either one of two input signals, INO_ or IN1_, can control both the forced voltage and the forced current. In this case, the two input signals represent alternate forcing values that can be selected with the serial interface. Alternatively, each input signal can be dedicated to control a single forcing function (i.e., voltage or current).

Ground, DUT Ground, IOS

The MAX9949/MAX9950 utilize two local grounds, AGND (analog ground) and DGND (digital ground). Connect AGND and DGND together on the PC board. In a typical ATE system, the PMU force voltage is relative to the DUT ground. In this case, reference the input voltages INO_ and IN1_ to the DUT ground. Similarly, reference IOS to the DUT ground. If it is not desired to offset the current control and measure voltages, connect IOS to the DUT ground potential.

Reference the MSR_ output to the DUT ground.





Figure 8. PMU Force Output Capability

Short-Circuit Protection

The FORCE_ output and SENSE_ input can withstand a short to any voltage between the supply rails.

Mode and Range Change Transients

The MAX9949/MAX9950 feature make-before-break switching to minimize glitches. The integrated voltage clamps also reduce glitching on the output.

DUT Voltage Swing vs. DUT Current and Power-Supply Voltages

Several factors limit the actual DUT voltage that the PMU delivers:

- The overhead required by the amplifiers and other integrated circuitry—this is typically 3.5V from each rail for no load current and 5V under full load
- The voltage drop across the current-range select resistor and internal circuitry in series with the sense resistor—at full current, the combined voltage drop is typically 2.75V

- 3) Variations in the power supplies—system implementation determines the variance
- 4) Variation of DUT ground vs. PMU ground—system implementation determines the variance

Neglecting the effects of the third and fourth items, Figure 8 demonstrates the force output capabilities of the PMU.

Figure 8 indicates that, for zero DUT current, the DUT voltage swings from (VEE + 3.5V) to (V_{CC} - 3.5V). For larger positive DUT currents, the positive swing drops off linearly until it reaches (V_{CC} - 5V) at full current. Similarly, for larger negative DUT currents, the negative voltage swing drops off linearly until it reaches (V_{EE} + 5V) at full current.

Settling Times and Compensation Capacitors

The data in the *Electrical Characteristics* table reflects the circuit shown in the block diagram that includes a single compensation capacitor (Cx) effectively across all the sense resistors. Placing individual capacitors, C_{RA}, C_{RB}, C_{RC}, C_{RD}, and C_{RE} directly across the sense resistors, R_A, R_B, R_C, R_D, and R_E, independently optimizes each range.

The combination of the capacitance across the sense resistors (Cx or C_{RA}, C_{RB}, C_{RC}, C_{RD}, and C_{RE}) and the main amplifier compensation comparator, C_{CM}, ensures stability into the maximum expected load capacitance while optimizing settling time.

Digital Inputs (SCLK, DIN, CS, LOAD) The digital inputs incorporate hysteresis to mitigate issues with noise, as well as provide for compatibility with opto-isolators that can have slow edges.

Chip Information

PROCESS: BICMOS

MAX9949/MAX9950



MAX9949 Pin Configuration

MAX9949/MAX9950



MAX9950 Pin Configuration

Package Information

For the latest package outline information and land patterns, go to www.maxim-ic.com/packages.

PACKAGE TYPE	PACKAGE CODE	OUTLINE NO.	LAND PATTERN NO.
64 TQFP-EPR	C64E-9R	<u>21-0162</u>	<u>90-xxxx</u>
64 TQFP-EP	C64E-6	<u>21-0084</u>	<u>90-xxxx</u>



Revision History

REVISION NUMBER	REVISION DATE	DESCRIPTION	PAGES CHANGED
2	3/09	Corrected timing diagrams and changed to lead-free package.	1, 13, 14
3	6/10	Updated <i>Absolute Maximum Ratings</i> section. Corrected timing diagrams so operation is more clearly understood. Bit names rather than bit numbers adopted.	2, 9, 11, 14–17

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