MRC Molecular Haematology Unit

UNIVERSITY OF OXFORD

MRC Weatherall Institute of Molecular Medicine

Methods in Haematopoietic Stem Cell Biology

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MRC WIMM DPhil Course November 2019

Learning Objectives

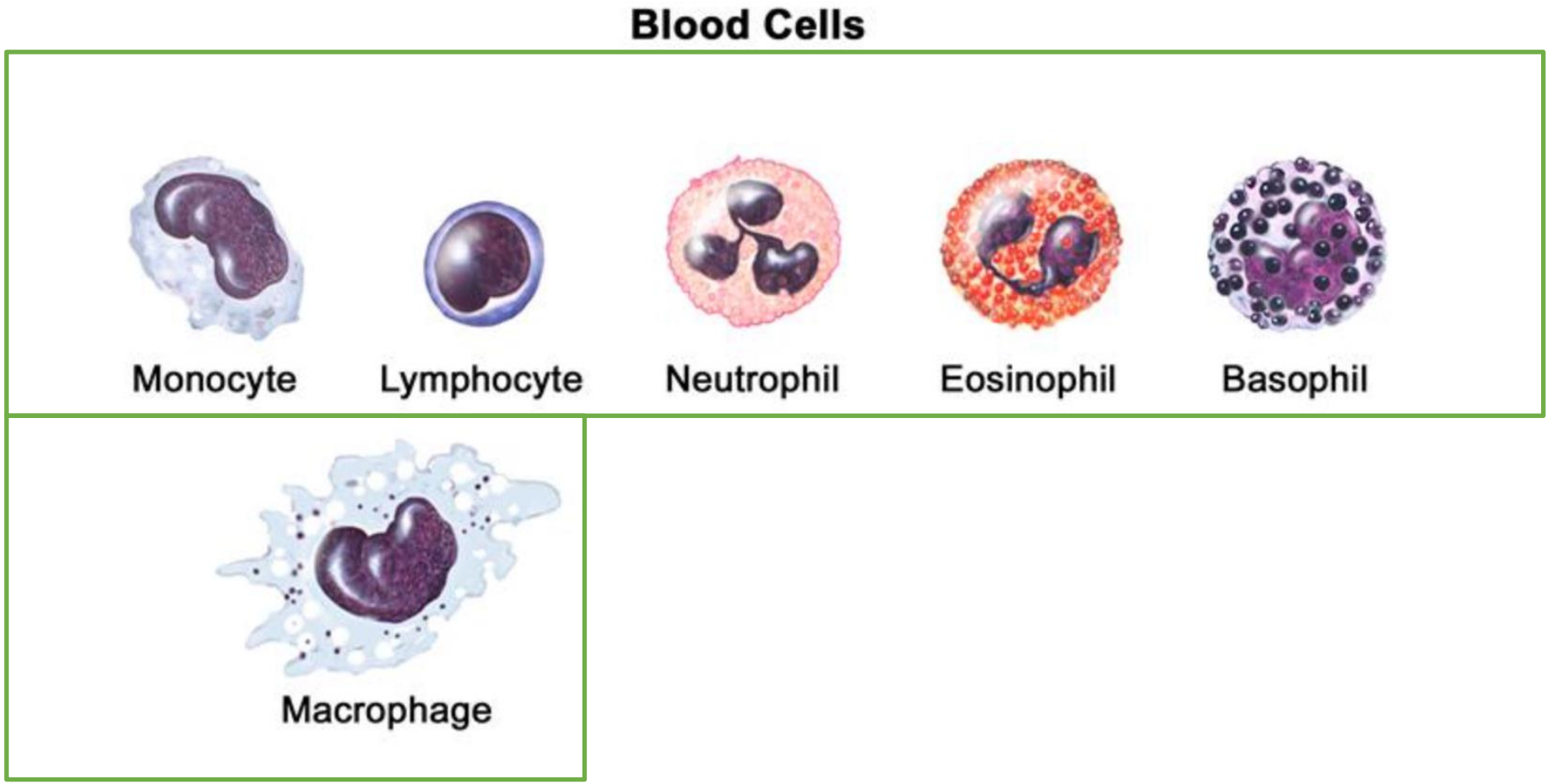
- What is a **haematopoietic stem cell (HSC)?**
- **Key concepts** in HSC biology during ontogeny and adult life
  - Definitions and properties of HSCs and progenitors
  - HSC niches
  - Intrinsic / extrinsic regulators
- **Experimental approaches** to study HSC biology
  - *In vitro*
  - *In vivo*
- **Cancer Stem cells**

What is **haematopoiesis?**

The process that generates blood cells of all lineages throughout life (from 3 weeks gestation)

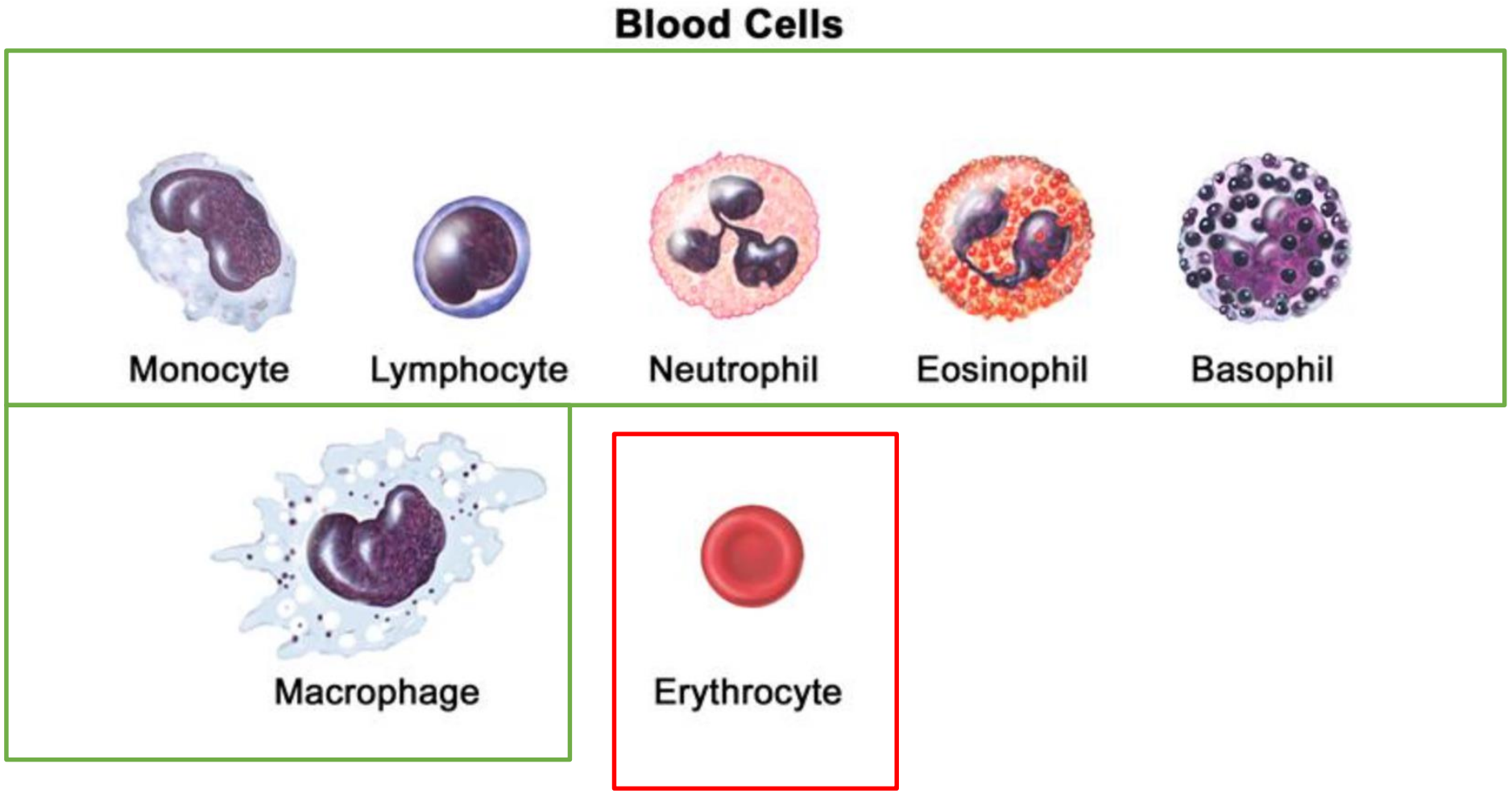
Blood cell lineages

White cells



Blood cell lineages

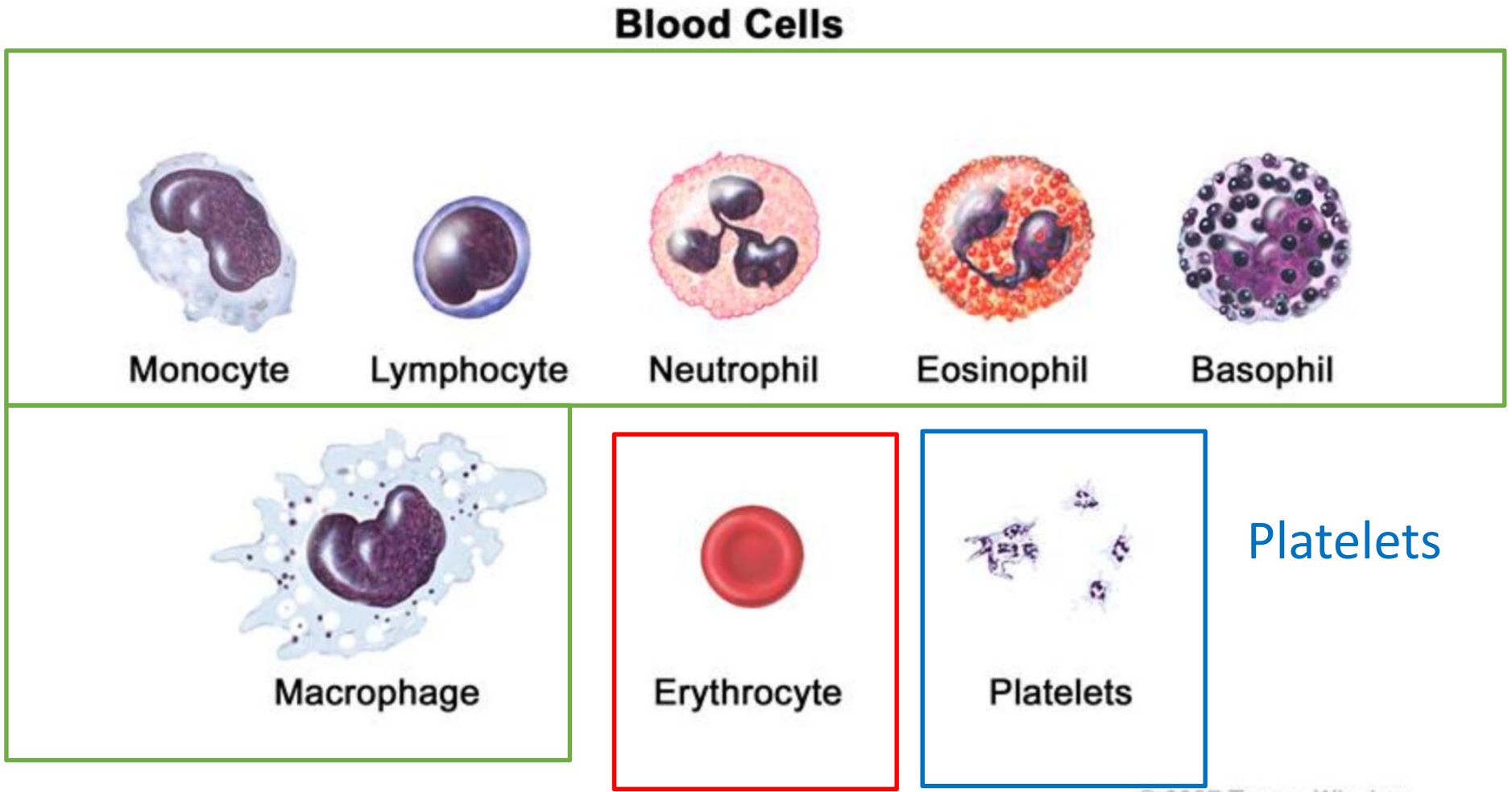
White cells



Red cells

Blood cell lineages

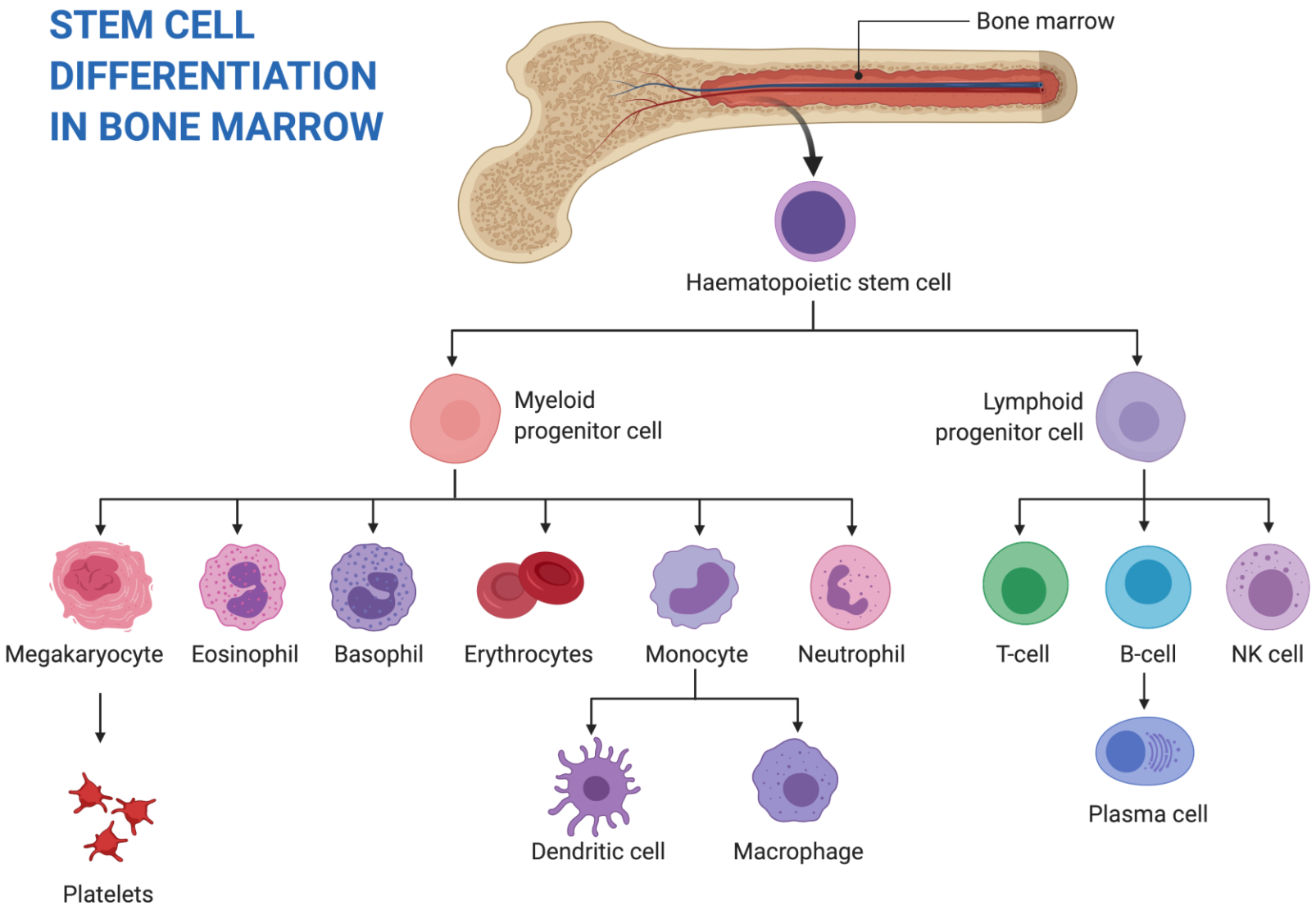
White cells



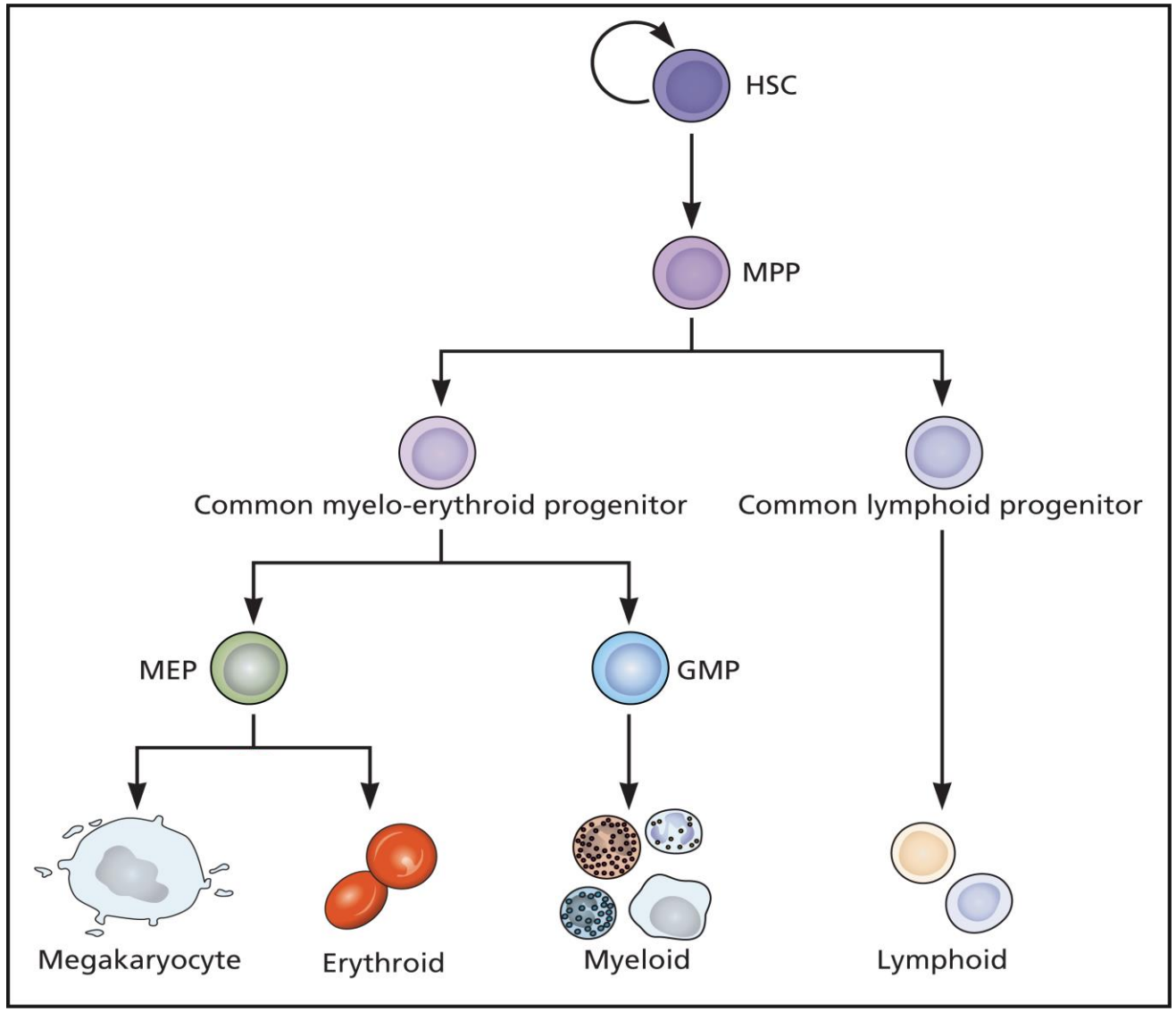
HSCs are arguably the best studied stem cell in mammals

- Easy of access
- Blood lineages are morphologically and immunophenotypically distinct
- Experimental assays now well developed
- Only stem cell therapy in routine clinical use
- While stem cell transplant is widely used, there are many limitations
  - Mortality <25%
  - Graft-versus-host-disease
  - Relapse

Haematopoiesis: classical hierarchical model

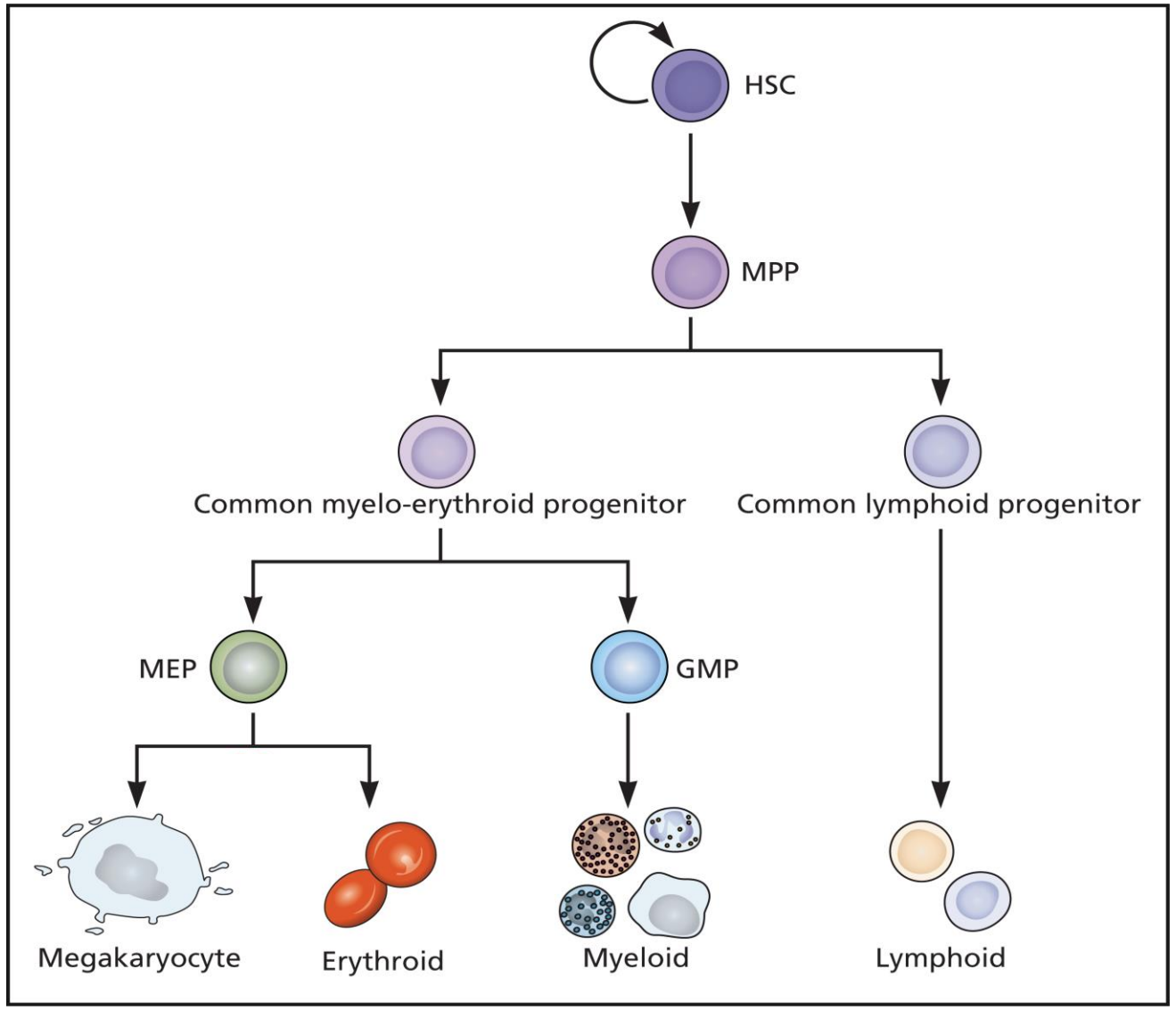


Haematopoietic stem cells



What are the key defining properties of an HSC?

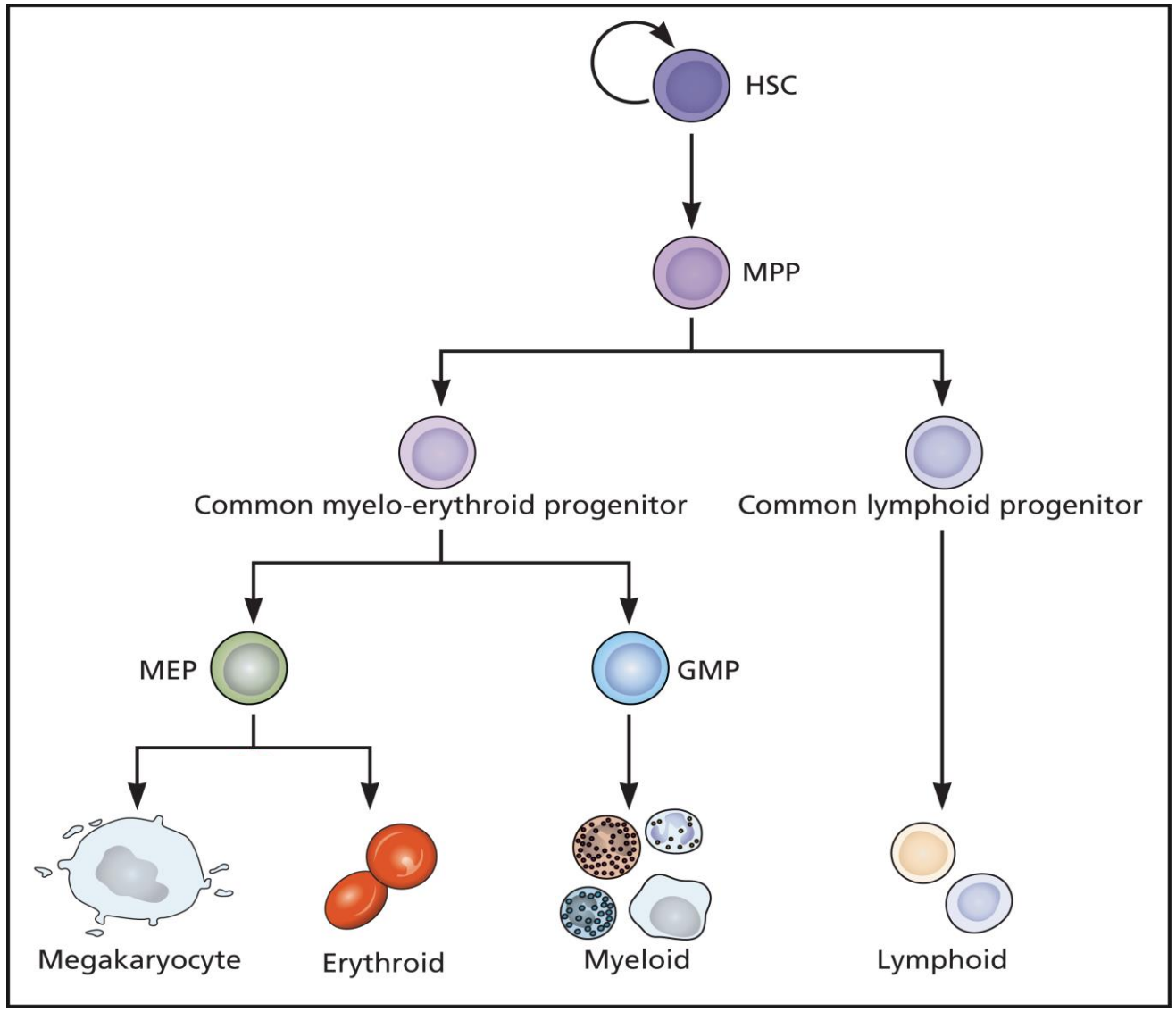
Haematopoietic stem cells



Properties of HSCs

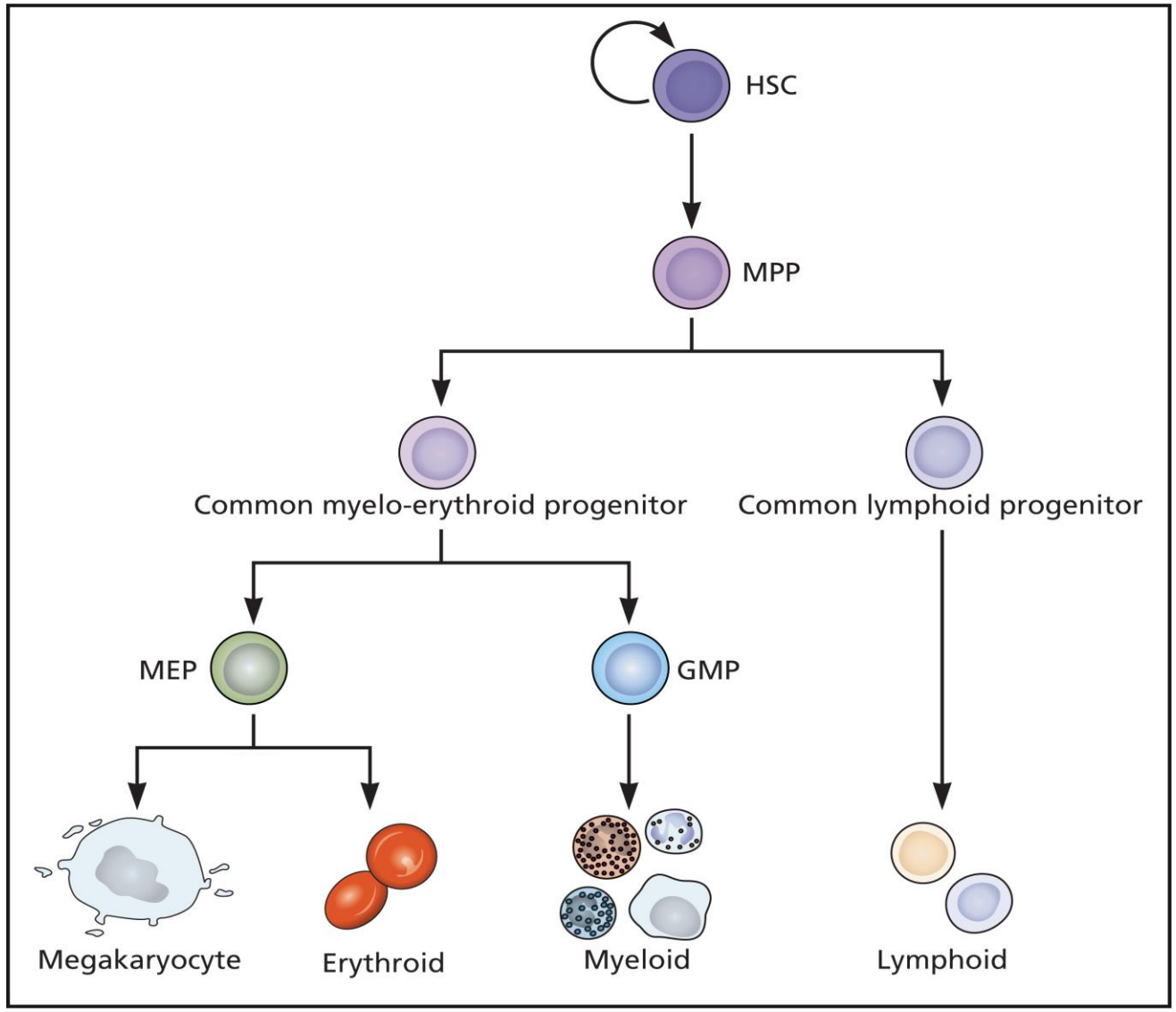
- Self renewal
- Multi-lineage differentiation
- When transplanted, can reconstitute life-long haematopoiesis

Haematopoietic **progenitor** cells



- Less self-renewal capacity (short term engraftment)
- Already made some lineage commitment decisions

Haematopoietic **progenitor** cells



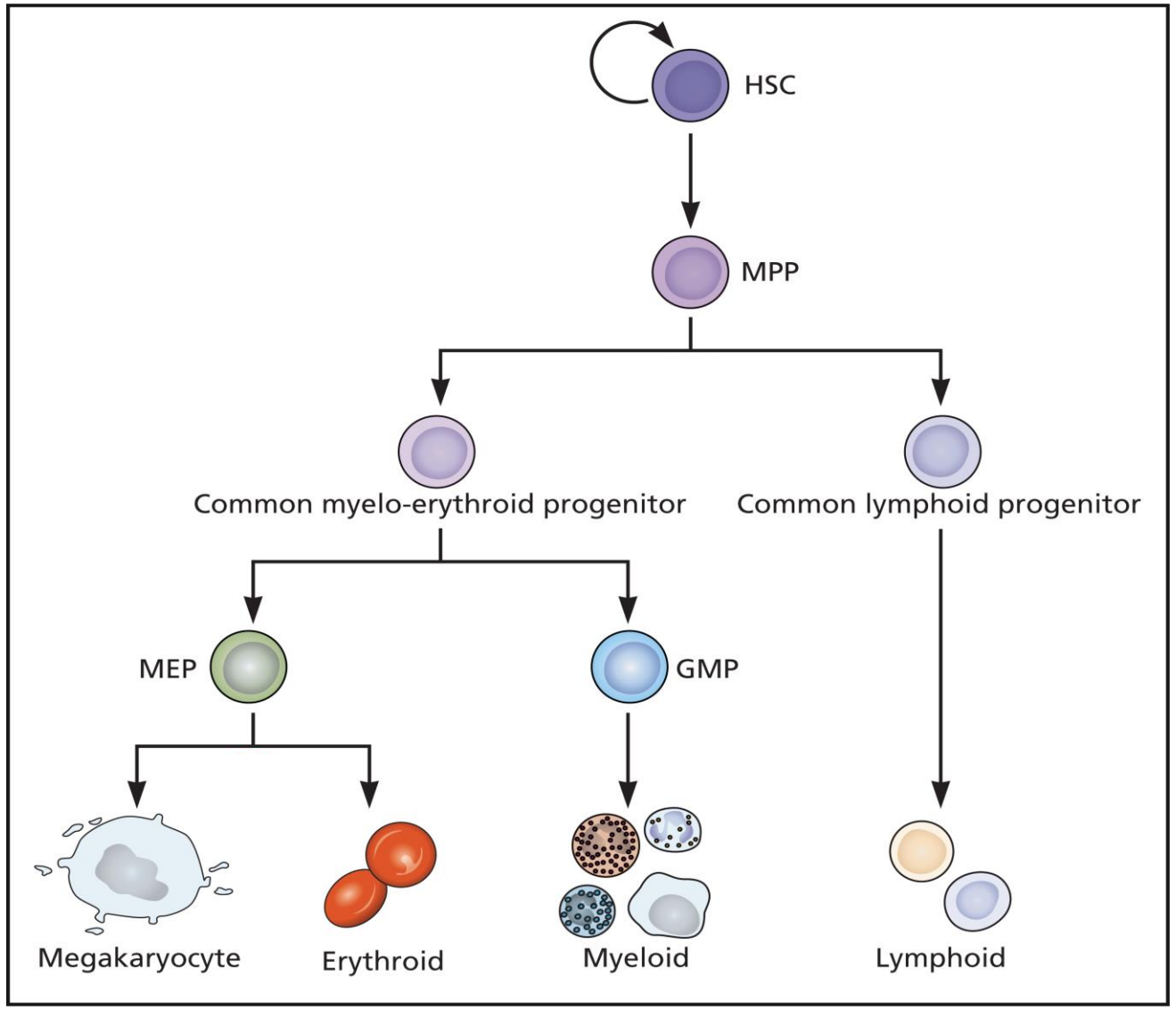
- Common **lymphoid** progenitor

(B, T, NK cells)

- Common **myeloid** progenitor

(granulocytes, erythroid, megakaryocyte and monocyte/macrophage)

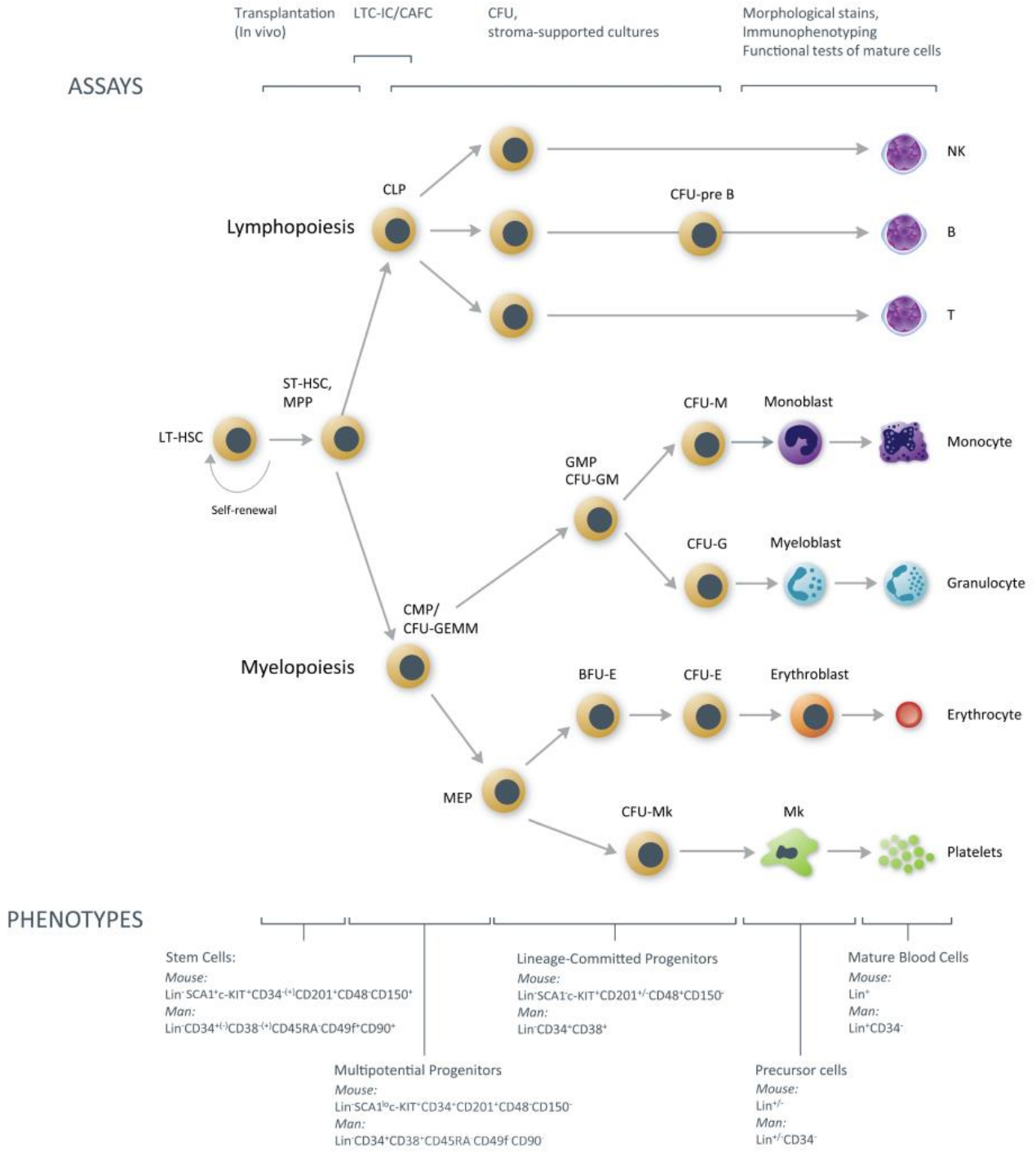
Haematopoietic stem/progenitor cells



Identified by their expression of cell surface markers

e.g. Human HSC = **CD34+**lineage-CD38-CD45RA-CD90+CD49f+

Identification of HSC/HSPCs: Human/mouse



B

Cell type	Mouse marker		Human marker
HSCs	LT-HSC	Lin^- $Sca\text{-}1^+$ $c\text{-}Kit^+$ $CD34^-$ $Flk2^-$	$CD34^+$ $CD38^-$ $CD90^+$ $CD45RA^-$ $CD49F^+$
	ST-HSC	$Line^-$ $Sca\text{-}1^+$ $c\text{-}Kit^+$ $CD34^+$ $Flt2^-$	
	MPPs	Lin^- $Sca\text{-}1^+$ $c\text{-}Kit^+$ $CD34^+$ $Flt2^+$	$CD34^+$ $CD38^-$ $CD90^-$ $CD45RA^-$ $CD49F^-$
SLAM-HSCs	SLAM-HSC	Lin^- $Sca\text{-}1^+$ $c\text{-}Kit^+$ $CD150^+$ $CD48^-$ $CD229^-$ $CD244^-$	
	SLAM-MPP	Lin^- $Sca\text{-}1^+$ $c\text{-}Kit^+$ $CD150^-$ $CD48^-$ $CD229^-$ $CD244^-$	
Progenitor cells	CLP	Lin^- $Flt2^+$ $IL7Ra^+$ $CD27^+$	$CD34^+$ $CD10^+$ $CD7^+$
	CMP	$Line^-$ $Sca\text{-}1^-$ $c\text{-}Kit^+$ $CD34^+$ $Fc\gamma RII/III^-$	$CD34^+$ $CD38^+$ $CD123^{med}$ $CD135^+$ $CD45RA^-$
	GMP	Lin^- $Sca\text{-}1^-$ $c\text{-}Kit^+$ $CD34^+$ $Fc\gamma RII/III^+$	$CD34^+$ $CD38^+$ $CD123^{med}$ $CD135^+$ $CD45RA^+$
	MEP	Lin^- $Sca\text{-}1^-$ $c\text{-}Kit^+$ $CD34^-$ $Fc\gamma RII/III^-$	$CD34^+$ $CD38^+$ $CD123^-$ $CD135^-$ $CD45RA^-$ $CD110^+$
Niche supporting cells	Mφ	$CD11b^+$ $Gr1^{low}$ $F4/80^+$ SSC^{low}	
	T cell	$CD3^+$	$CD4^+$ $CD25^+$ $CD127^{low}$ $CD45RA^{+/-}$
	B cell	$CD45R/B220^+$	
	Erythrocyte	$CD45^-Ter119^+$	
	EC	$CD45^-Ter119^-CD31^+$	
	BMSC	$CD45^-Ter119^-CD31^-$ $LepR^+$	$CD45^-$ $CD34^-$ $CD73^+$ $CD105^+$ $CD90^+$
	OB	$CD45^-Ter119^-CD31^-$ $Sca1^-$ $CD51^+$	

Key markers
HUMAN – CD34, CD38

MOUSE – LSK, CD34-

Lim & Son, 2017

Table 1

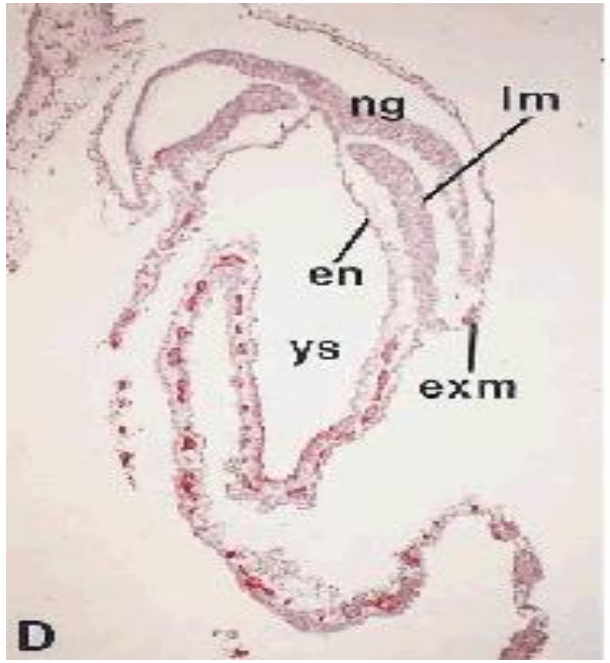
Unique and overlapping commonly used stem cell terms and definitions

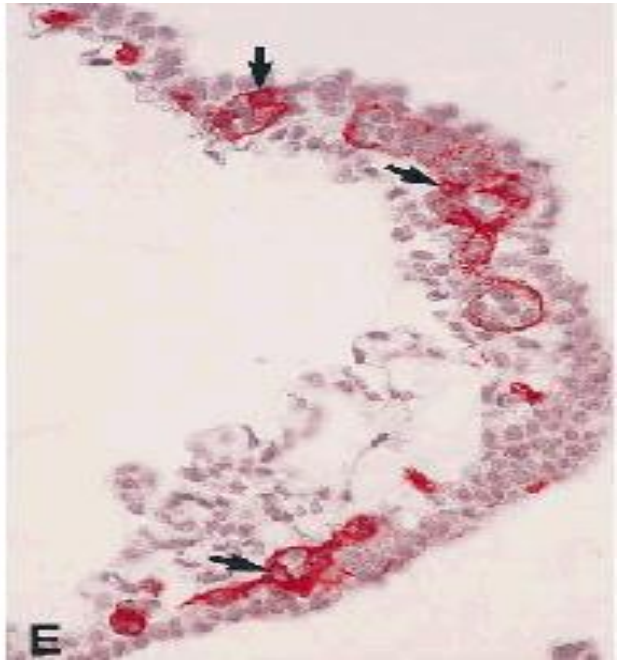
Term	Widely accepted definition
LT-HSC	Cells able to reconstitute all five types of mature blood cells in recipient mice over the long term (≥16-weeks after transplantation) and in secondary and tertiary transplants[28]
Intermediate term repopulating HSC (IT-HSC)	Cells that reconstitute multi-lineage blood cells over the medium term (6-8 months), but show some loss of self-renewal in secondary transplant recipients[28]
Short term repopulating HSC (ST-HSC)	Cells that transiently reconstitute multiple blood cell types for up to 8 weeks in transplant recipients, or in which one or more donor-derived lineages disappear before 24 weeks after primary transplant
Lineage priming	Expression of a transcriptional program associated with potential for differentiation to mature cells of a specific lineage in a multi/oligo-potent cell
Lineage bias	Multi/oligo-potent cells that preferentially give rise to a single lineage but retain potential for alternative differentiation
Lineage restricted/committed	Oligo/unipotent cells not able to give rise to cells of certain lineages
Lineage potential	The mature lineages that a cell ***has the potential to*** give rise depending on external stimuli
Lineage fate	The lineage that a stem/progenitor will give rise to *in vivo*

Sites of haematopoiesis: **embryonic life**

First signs are seen in the yolk sac at 3 weeks of gestation

PRIMITIVE HAEMATOPOIESIS



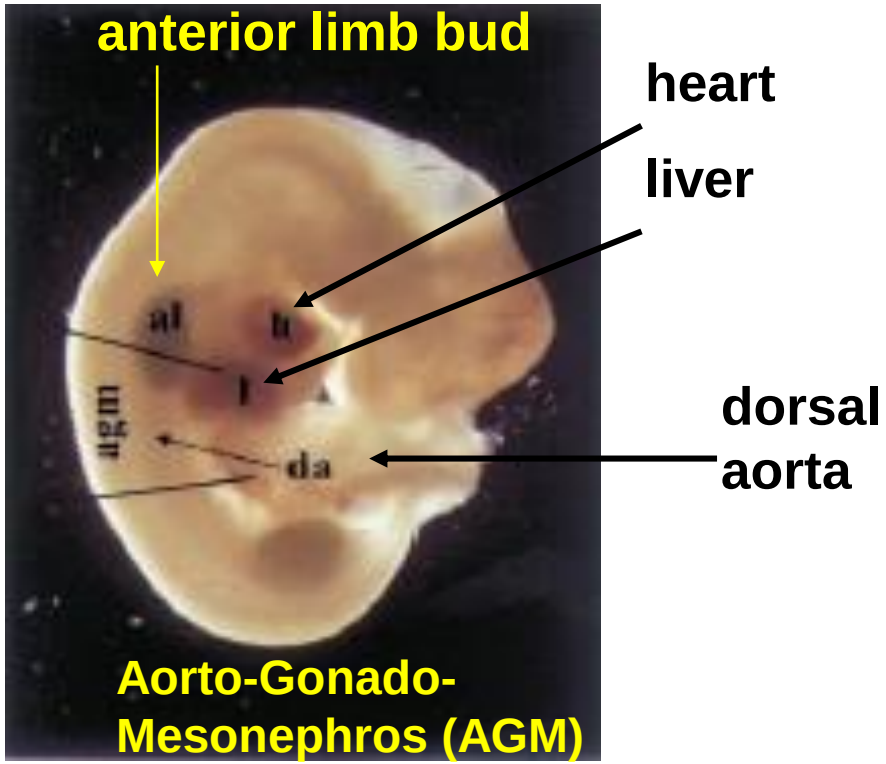


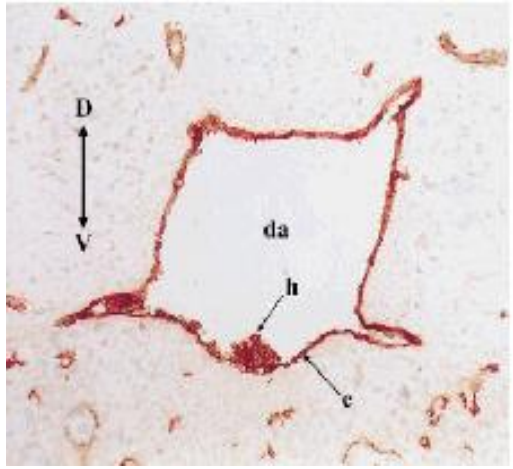
Immunostaining with anti-CD34 antibody marks haemopoietic stem/ progenitors cells & endothelial cells

Sites of haematopoiesis: **embryonic life**

DEFINITIVE HAEMATOPOIESIS begins in the aorto-gonado-mesonephros (AGM) at 5 weeks gestation

34-day human embryo



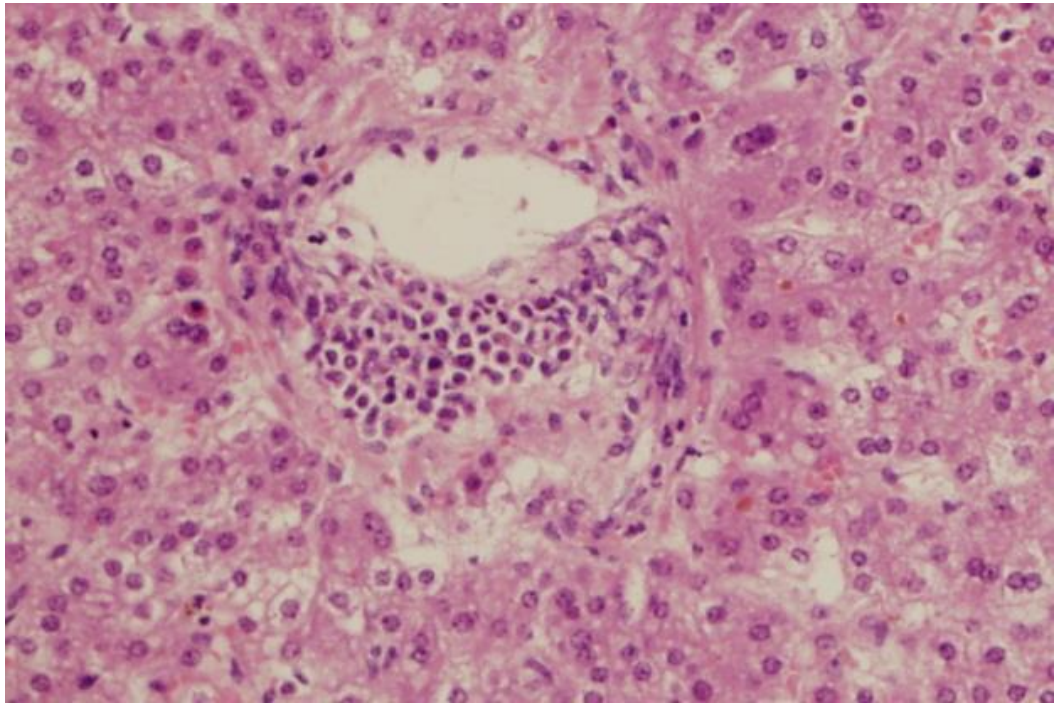


Cross section through the dorsal aorta to show haemopoietic cells (h) in the AGM (stained with CD34)

Sites of haematopoiesis: **embryonic life**

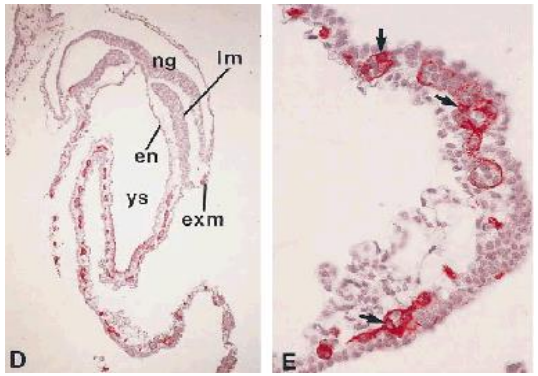
DEFINITIVE HAEMATOPOIESIS in the fetal liver begins at 7-8 weeks

This is the main site of haematopoiesis in fetal life



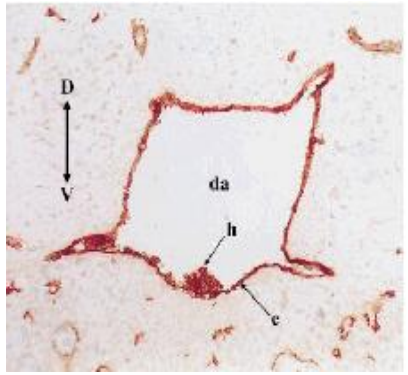
Sites of haematopoiesis: **embryonic life**

YOLK SAC



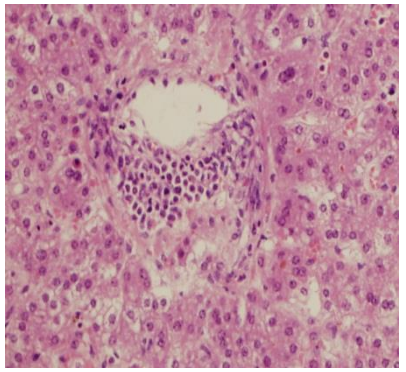
Generation of HSC
Mainly erythropoiesis

AGM



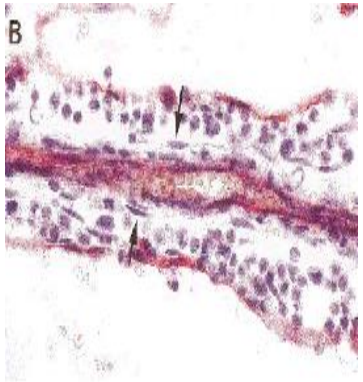
Generation of HSC
No expansion of HSC

LIVER



HSC maintenance
HSC expansion

BONE MARROW



Main site from 6-7 months of fetal life and after birth

3 wks — **5 wks** — **7-8 wks** — **12 wks**

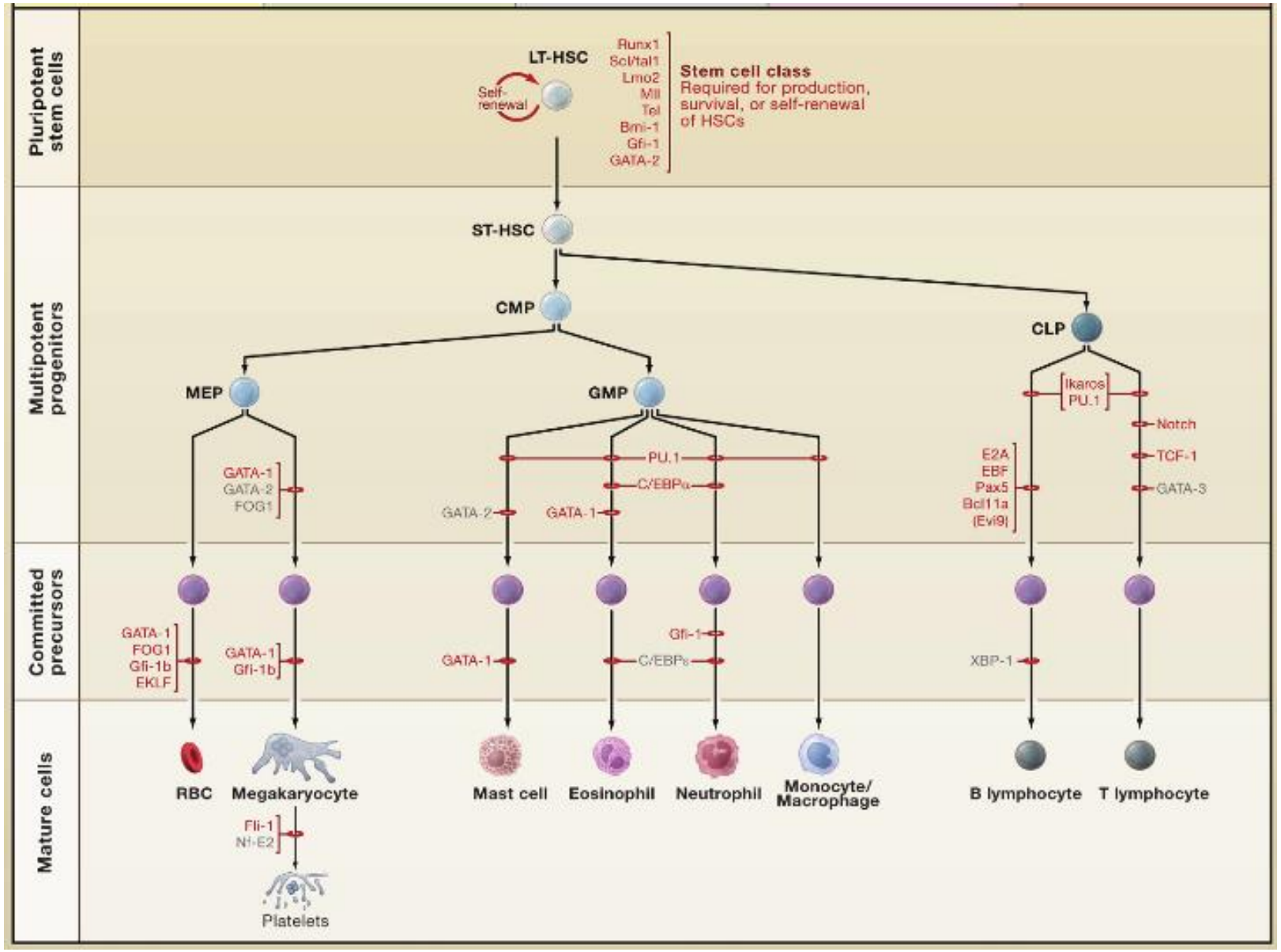
Primitive

Definitive haemopoiesis

Regulation of haematopoiesis

- Cell intrinsic
- Cell extrinsic

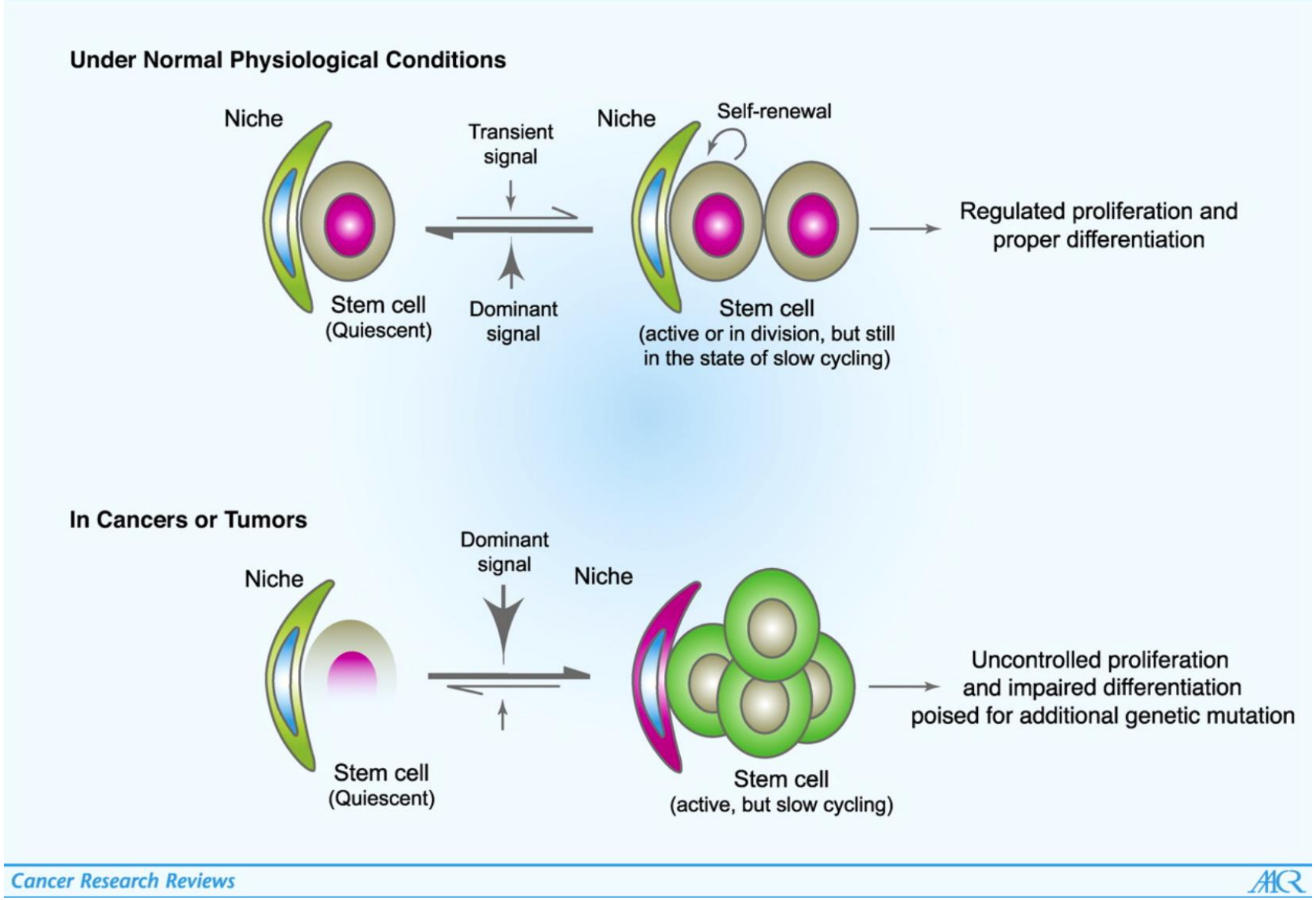
Cell intrinsic controls on haematopoiesis

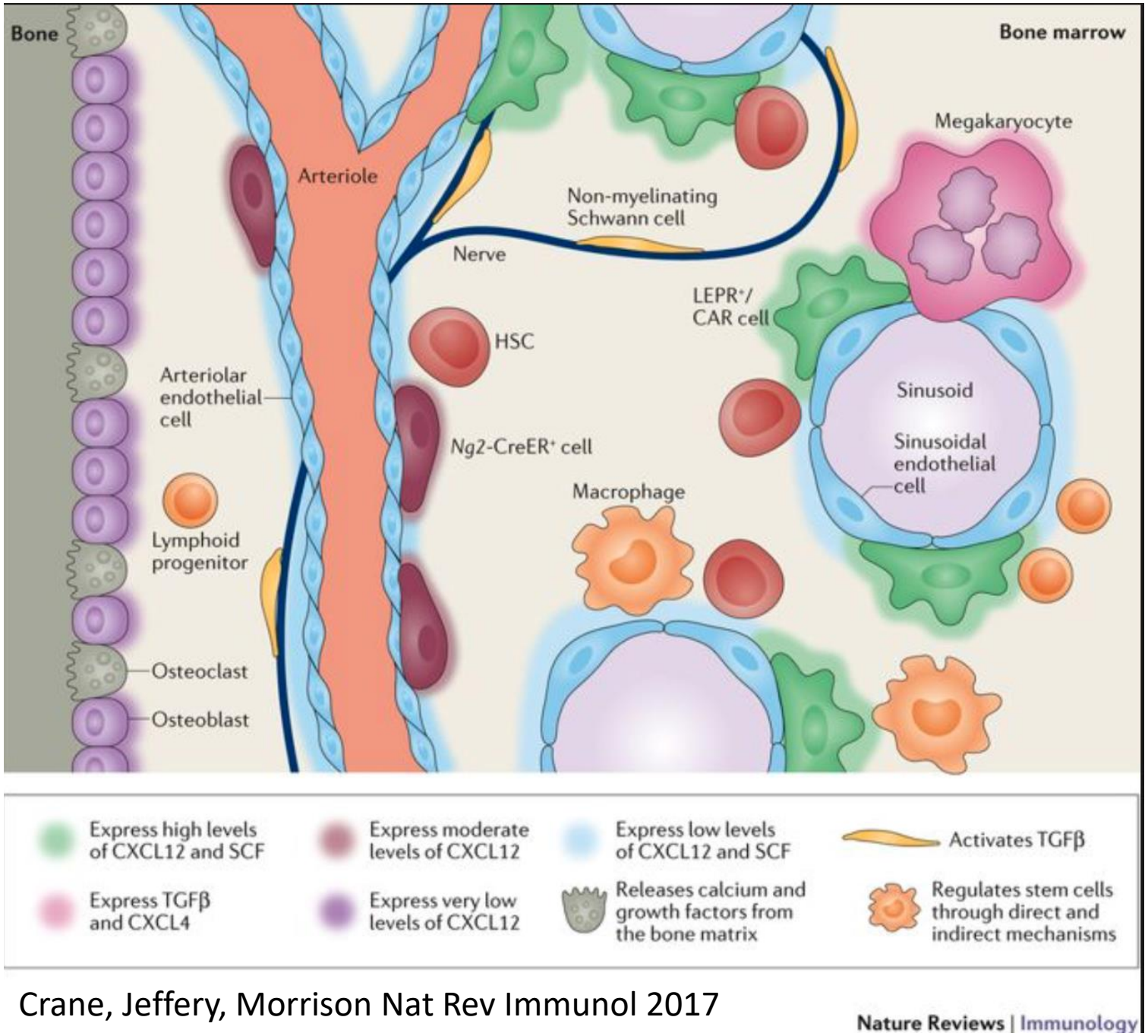


External control: role of microenvironment in haematopoiesis

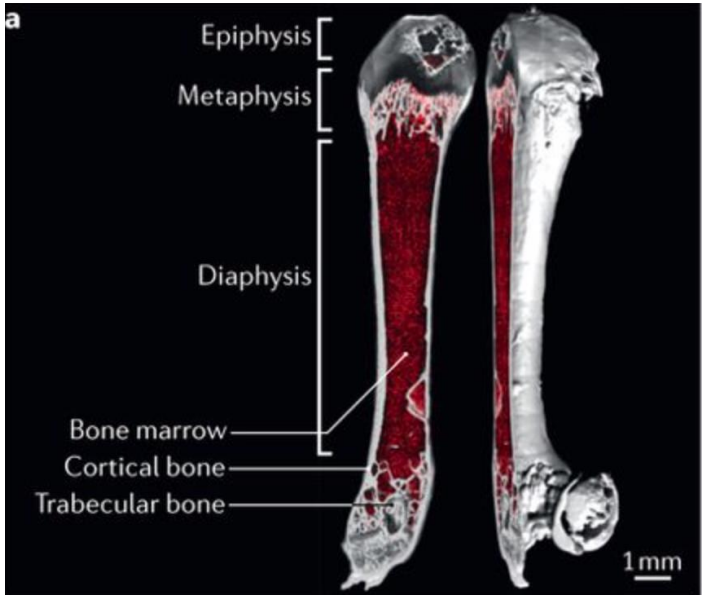
- Produce growth factors
- Support and regulate balanced self-renewal and differentiation
- To increase mature cells in response to increased demand
- Physical support
- Homing of stem and progenitor cells

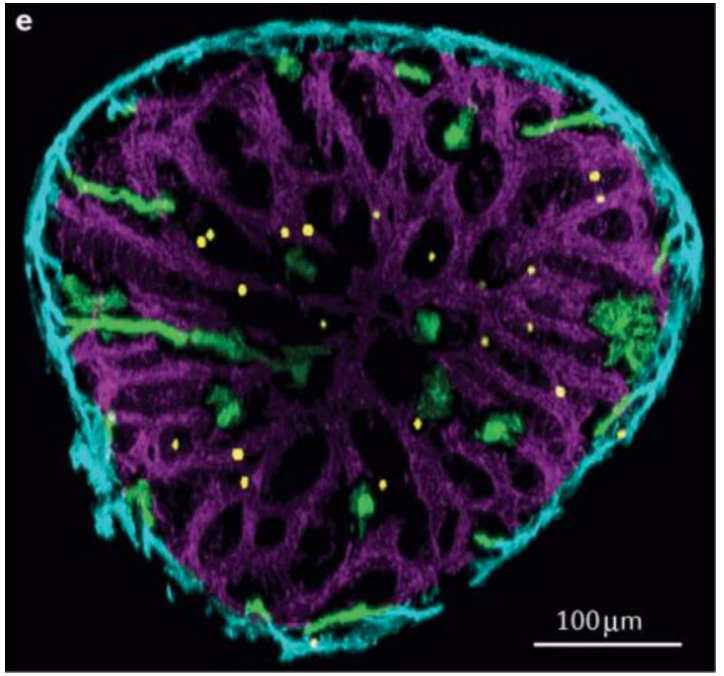
Niche-HSC interactions





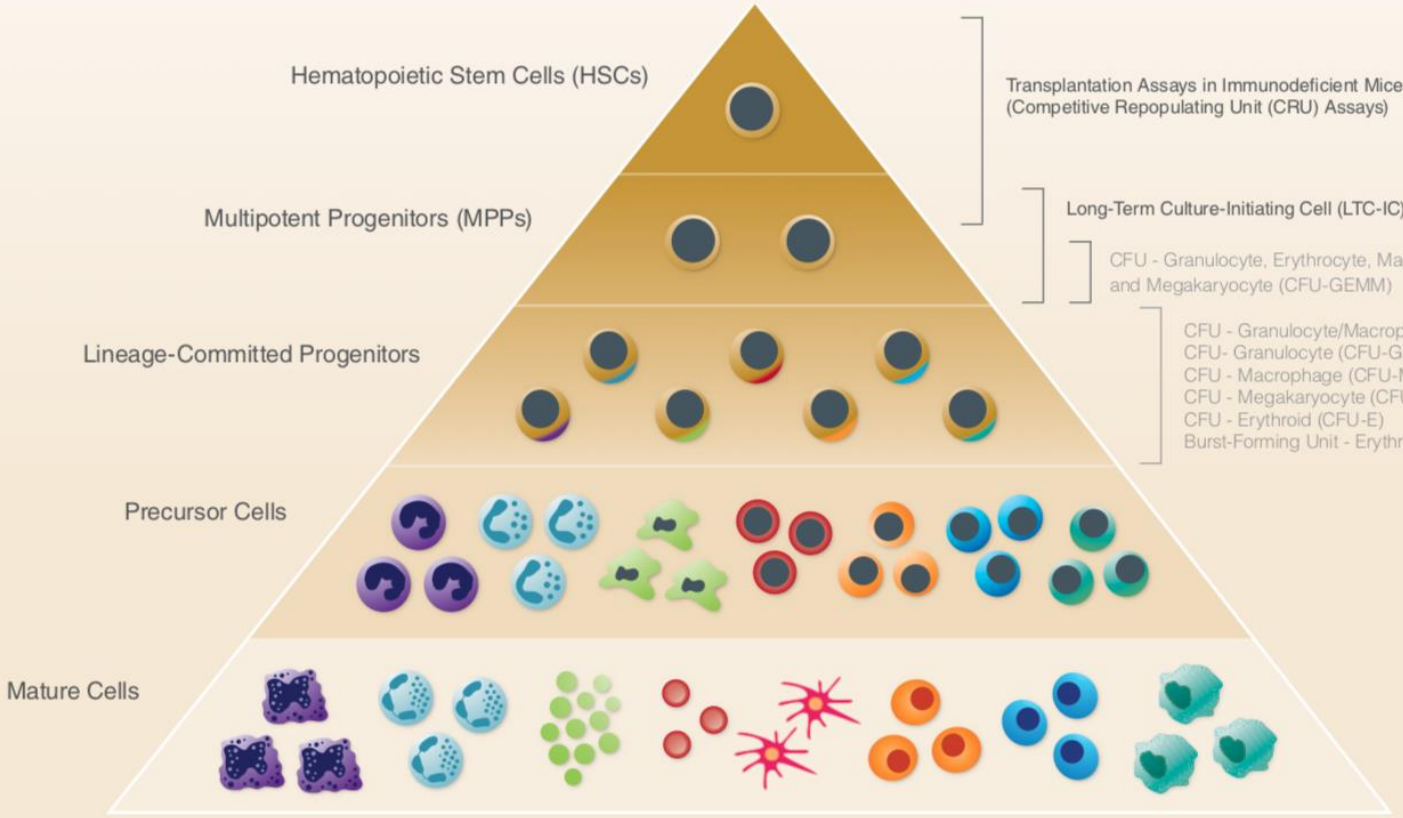
Crane, Jeffery, Morrison Nat Rev Immunol 2017





Experimental methods to study HSCs

Hematopoietic Cell Compartments and Assays for Their Identification



Transplantation Assays in Immunodeficient Mice
(Competitive Repopulating Unit (CRU) Assays)

Long-Term Culture-Initiating Cell (LTC-IC) Assays with MyeloCult™

CFU - Granulocyte, Erythrocyte, Macrophage and Megakaryocyte (CFU-GEMM)

CFU - Granulocyte/Macrophage (CFU-GM)
CFU- Granulocyte (CFU-G)
CFU - Macrophage (CFU-M)
CFU - Megakaryocyte (CFU-Mk)
CFU - Erythroid (CFU-E)
Burst-Forming Unit - Erythroid (BFU-E)

Colony-Forming Unit (CFU) Assays with MethoCult™

Expansion and Differentiation Cultures with StemSpan™

Immunophenotyping
Functional Tests
Morphological Stains

References

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Experimental methods in HSC biology


QUIZ
TIME

Experimental methods in HSC biology

Which of the following is a ‘gold standard’ **stem cell** assay?

(1) Single cell RNA-sequencing

(2) Single cell colony forming assay

(3) Injection of a single cell into irradiated mouse and determination of lineage read out

(4) Single cell ATAC-sequencing

Experimental methods in HSC biology

- Which of the following cell surface markers are frequently used to identify multipotent stem/progenitor cells in humans?
  - (A) CD34
  - (B) Sca1
  - (C) cKIT
  - (D) CD38
  - (E) CD90

Experimental methods in HSC biology

Which of the following sentences is *not* true

(A) Haematopoiesis is first observed in the AGM region around 5 weeks gestation

(B) The bone marrow is the primary site of haematopoiesis from the 2nd trimester

(C) Haematopoiesis can be observed in the spleen, liver and skin in certain types of blood malignancies

(D) Platelets are produced in the lung


QUIZ
TIME

Experimental methods to study HSCs

- Stem cell assays to confirm ***multipotency***
  - Single cell transplantation of human cells into immunodeficient mice (serial transplantation)
  - Long term culture-initiating cell (LTC-IC) assays
  - Lineage tracing and barcoding approaches

- Methods to **determine lineage potential** of stem and progenitor cells
  - What lineages can this cell produce?
    - Colony forming assays (e.g. Methocult)
    - Liquid culture assays (supportive media with expansion/differentiation cytokines)

- **‘Phenotypic’ assays**
  - Immunophenotyping / proteomics
  - Gene expression assays

Need for a single cell approach

Bulk analysis

Information is ‘averaged’

How do you determine if a population is homogeneous?

Is any population truly homogeneous??

Unable to understand functional read-outs and to properly compare two populations using ‘bulk’ assays

Need for a single cell approach

Bulk analysis

Information is ‘averaged’

Single cell analysis

Unveil rare cell populations
Cellular hierarchies
Combinatorial patterns of gene expression

Need for a single cell approach

Bulk analysis

Information is ‘averaged’

Jnr Scientists a, b and c

Single cell analysis

Unveil rare cell populations
Cellular hierarchies
Combinatorial patterns of gene expression

3D context/spatial positioning

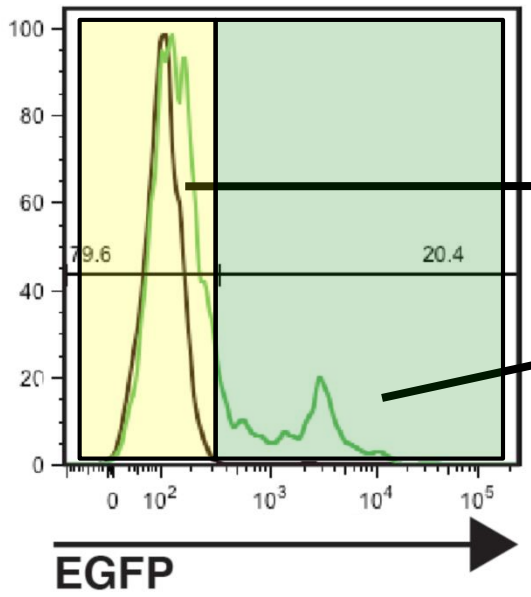
Organization in native context is crucial to understand cell-cell interactions

Single cell transplantation to identify lineage priming

- 1st in vivo transplantation assay was developed in 1950s by Ford et al (1956) and McCulloch & Till 1960
- CFU-S: colony forming unit-spleen cells
  - Cells injected into an irradiated recipient formed macroscopic splenic colonies 1-3 weeks later
  - Not a stem cell assay

- **Long term repopulating assays**
  - Usually done as competitive repopulation assay, to measure a population with unknown repopulating ability against competitor whole BM containing a known number of HSC → calculate the repopulating units
  - Frequency of HSC can be measured using a limiting dilution assay (dilutions of the test cells against constant number of competitors, measure the number of mice that are reconstituted)

Single cell transplantation to identify lineage priming



VWF-EGFP– or +
LT-HSCs (CD45.2)

CD45.1 wild type
competitor bone marrow

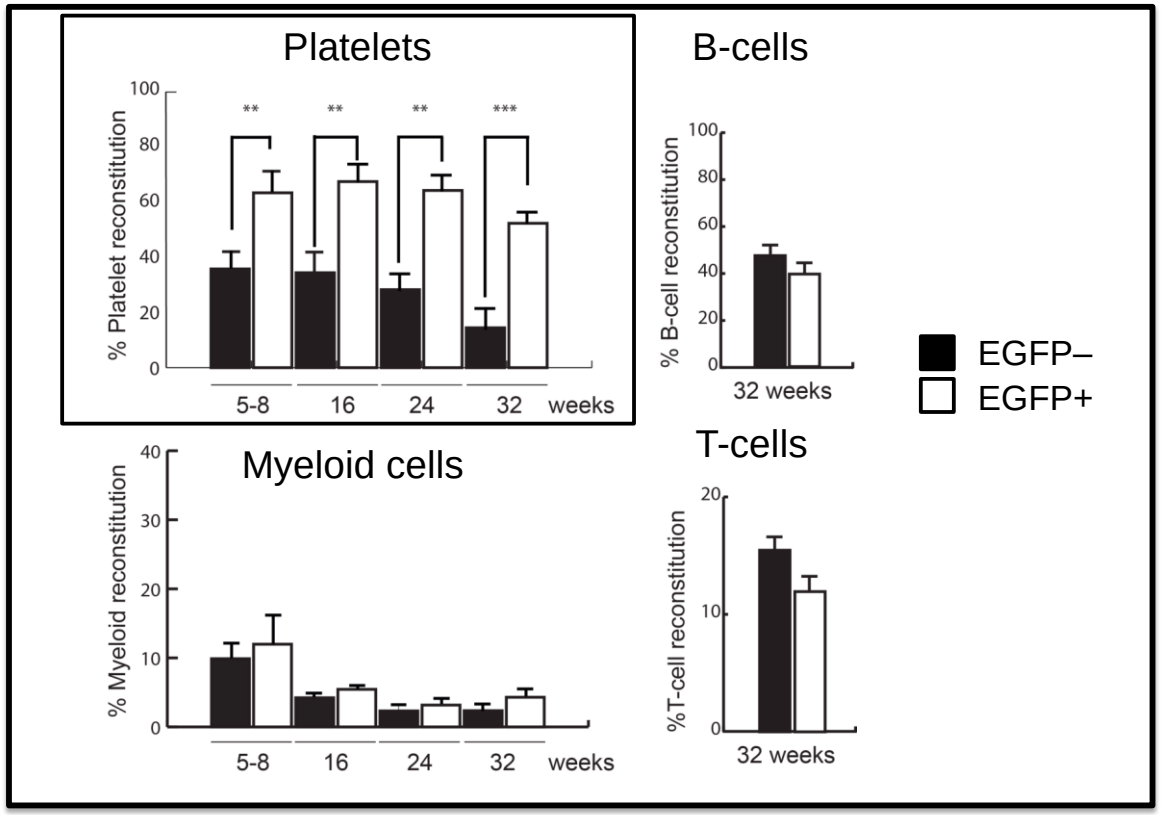
CD45.1 lethally
irradiated recipient

LETTER

doi:10.1038/nature12495

Platelet-biased stem cells reside at the apex of the haematopoietic stem-cell hierarchy

Alejandra Sanjuan-Pla[1,2], Iain C. Macaulay[3,4], Christina T. Jensen[3,4], Petter S. Woll[3,4], Tiago C. Luis[3,4], Adam Mead[3,4], Susan Moore[1,2], Cintia Carella[2], Sahoko Matsuoka[3,4], Tiphaine Bouriez Jones[3,4], Onima Chowdhury[3,4], Laura Stenson[3,4], Michael Lutteropp[3,4], Joanna C. A. Green[3,4], Raffaella Facchini[3,4], Hanane Boukarabila[3,4], Amit Grover[3], Adriana Gambardella[3], Supat Thongjuea[3], Joana Carrelha[3,4], Paul Tarrant[3,4], Deborah Atkinson[3,4], Sally-Ann Clark[3,4], Claus Nerlov[1,2,3]* & Sten Eirik W. Jacobsen[3,4]*

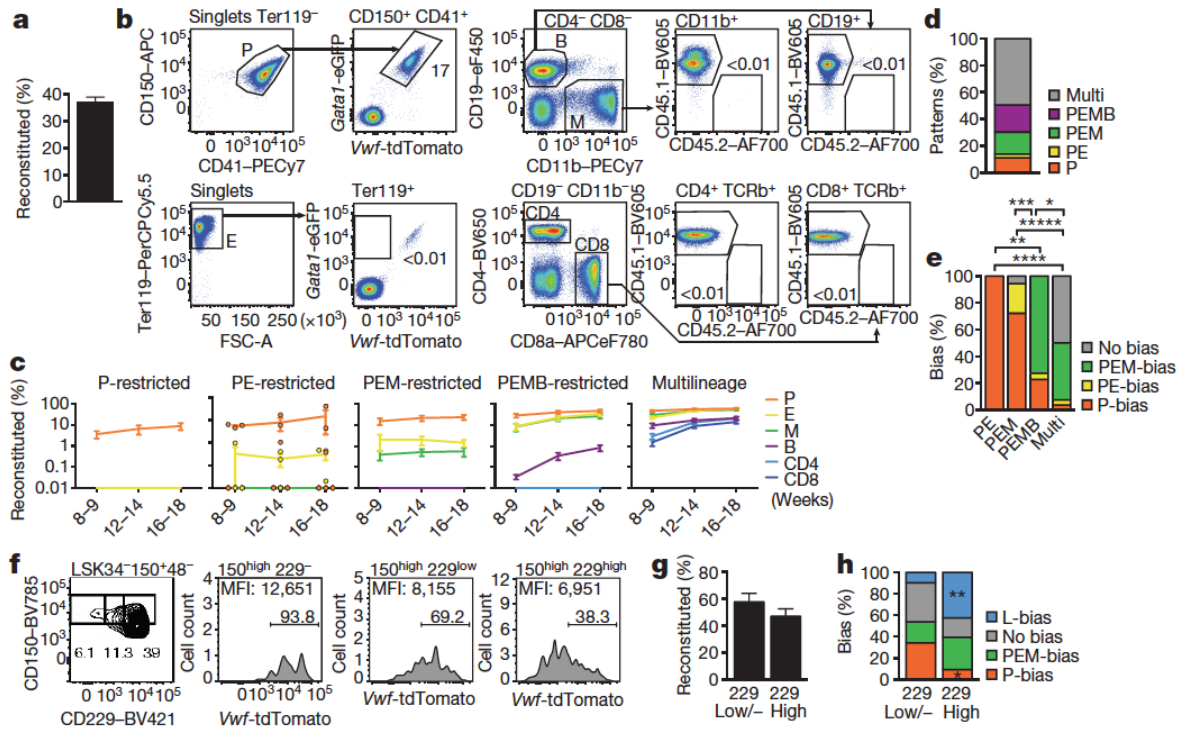


LETTER

doi:10.1038/nature25455

Hierarchically related lineage-restricted fates of multipotent haematopoietic stem cells

Joana Carrelha[1,2], Yiran Meng[1,2], Laura M. Kettyle[3,4], Tiago C. Luis[1,2], Ruggiero Norfo[1,2], Verónica Alcolea[1,2], Hanane Boukarabila[1,2]†, Francesca Grasso[4,5], Adriana Gambardella[2], Amit Grover[2], Kari Högstrand[3,4], Allegra M. Lord[3,4], Alejandra Sanjuan-Pla[2]†, Petter S. Woll[4,5], Claus Nerlov[2]* & Sten Eirik W. Jacobsen[1,2,3,4,5]*

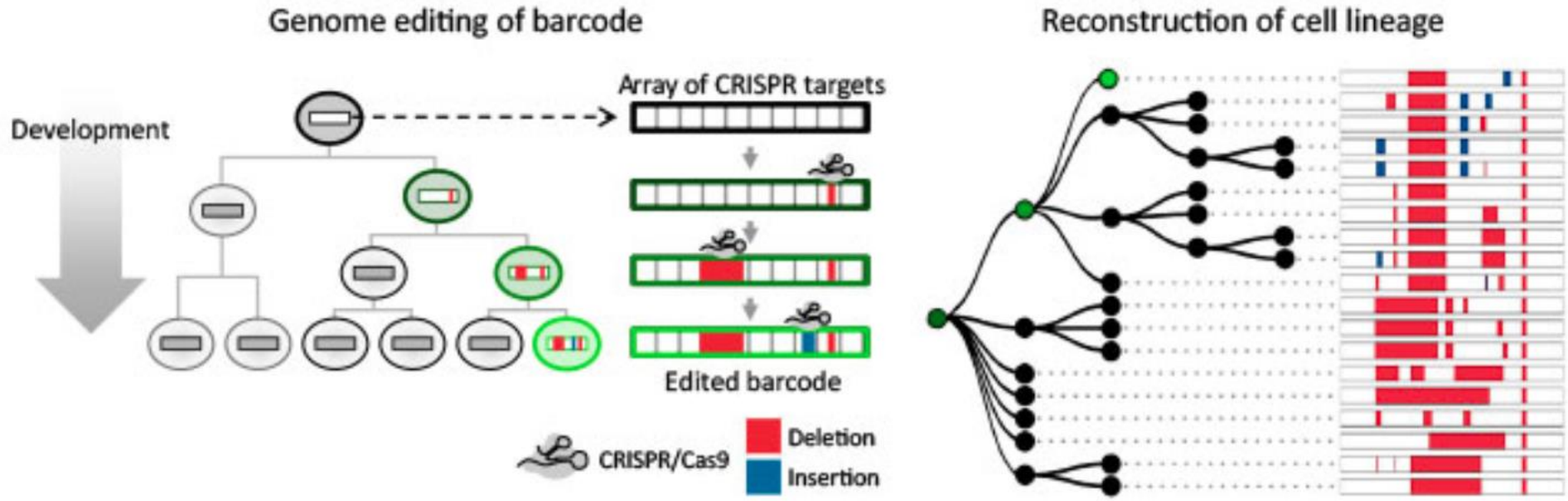


Considerations in these expts

- Cut off for engraftment is arbitrary – 1% for all lineages?
- Time point for analysis?
- Differences in genetic background of mice
- What method has been used to identify the donor vs recipient cells and how robust is this
- Can be difficult to determine whether a phenotype is due to differences in the HSC or in their potential to produce progeny
- Expensive and use a lot of mice!
- Assay also dependent on homing and engraftment potential of HSCs
- BM microenvironment is perturbed
- Not all lineages can be thoroughly assessed e.g. Mk-E

Lineage tracing / barcoding assays

- CRISPR-Cas9: ‘dropping genetic breadcrumbs’ into developing cells



GESTALT – Science 2016. CRISPR-Cas9 used to introduce a 300 bp ‘barcode’ into dividing cells and cell progeny then tracked as they accumulate mutations. Progeny cells then collected and DNA amplified to ‘read’ the barcode and reconstruct the lineage tree

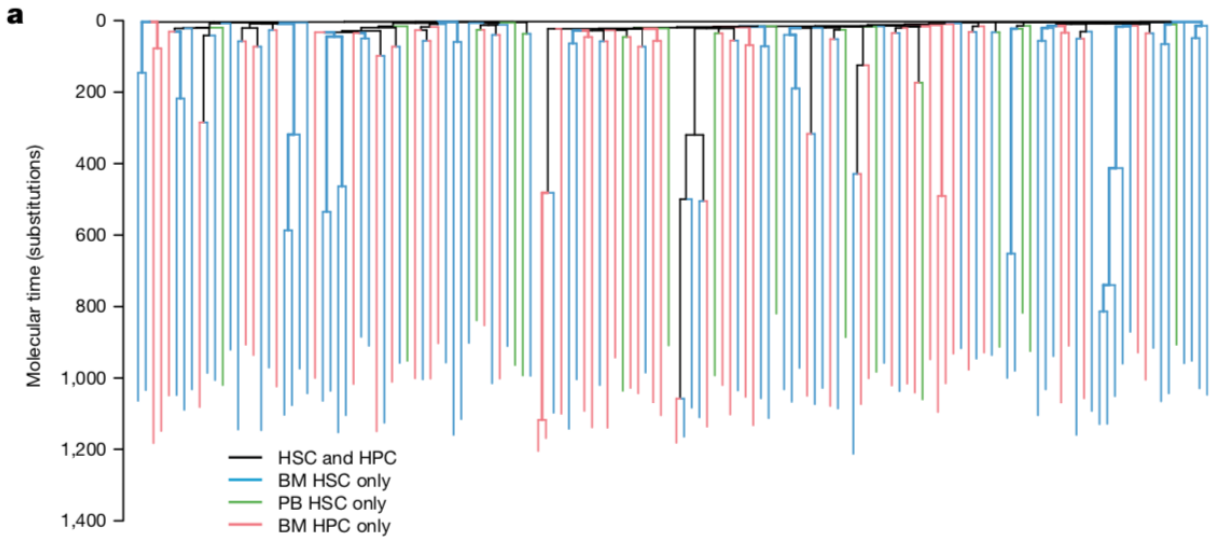
Acquisition of somatic barcodes confers an endogenous ‘barcode’

ARTICLE

https://doi.org/10.1038/s41586-018-0497-0

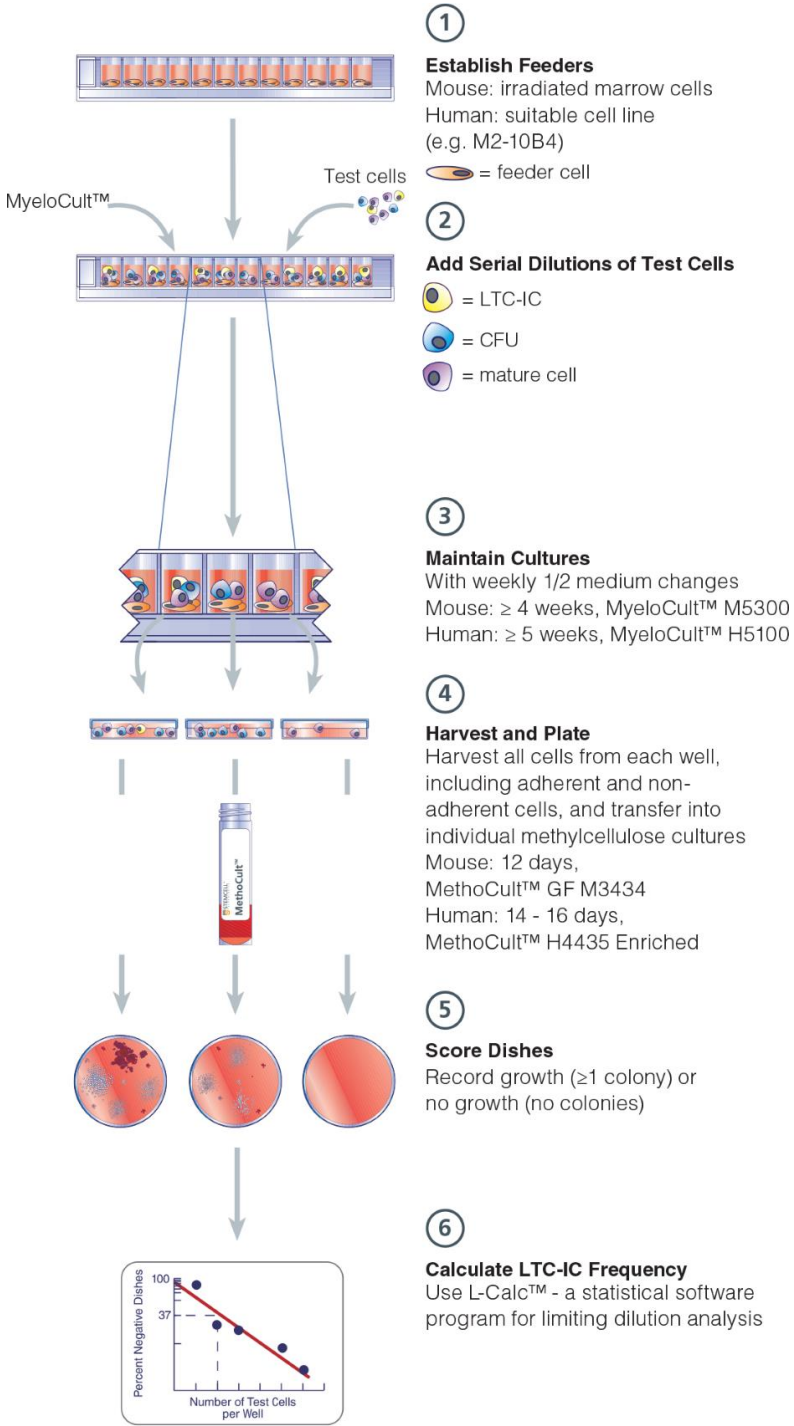
Population dynamics of normal human blood inferred from somatic mutations

Henry Lee-Six[1], Nina Friesgaard Øbro[2], Mairi S. Shepherd[2], Sebastian Grossmann[1], Kevin Dawson[1], Miriam Belmonte[2], Robert J. Osborne[1], Brian J. P. Huntly[2], Inigo Martincorena[1], Elizabeth Anderson[1], Laura O’Neill[1], Michael R. Stratton[1], Elisa Laurenti[2], Anthony R. Green[2,3]*, David G. Kent[2,3]* & Peter J. Campbell[1,3]*



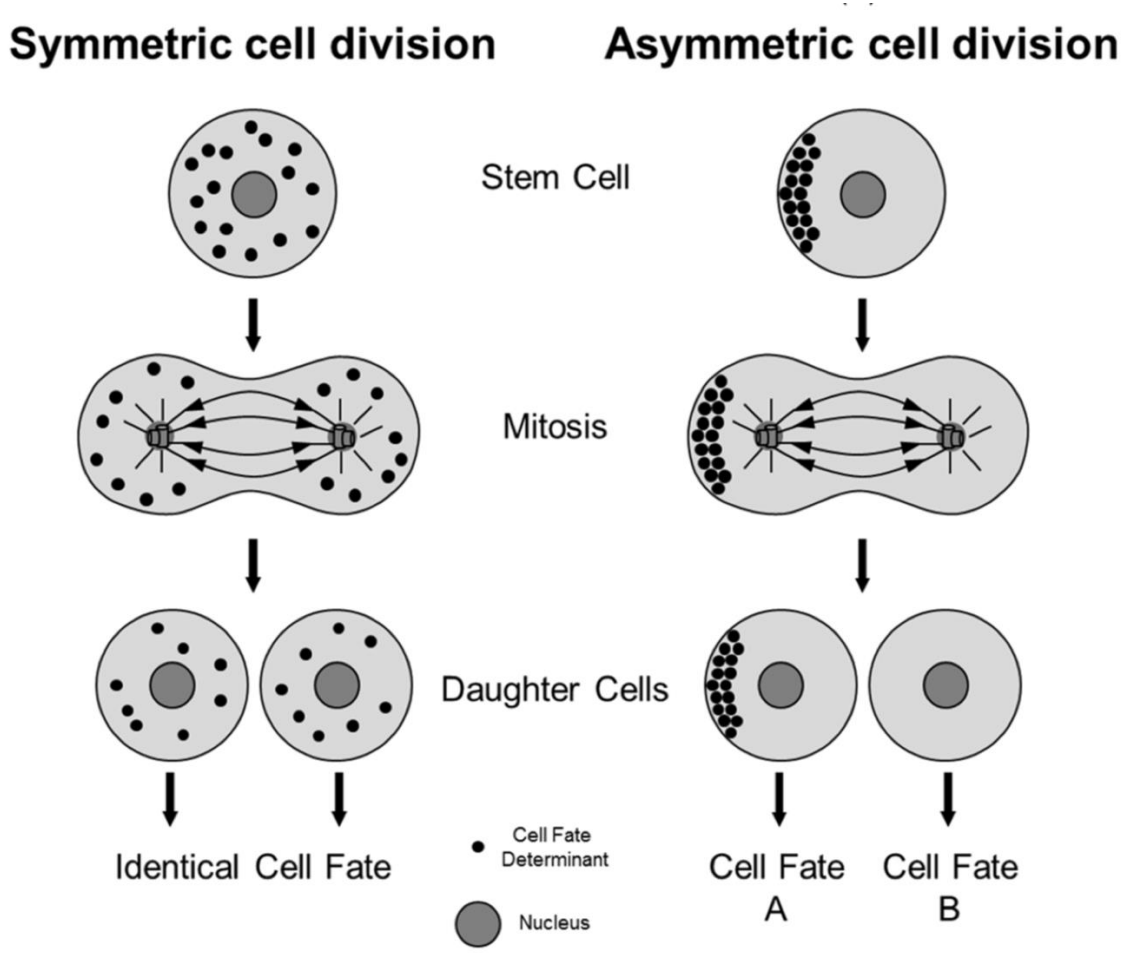
In vitro stem cell assay: Long term Colony-initating cell assay (LTC-IC)

Plate cells on stromal support cells for 4-6 weeks
Then transfer to methylcellulose to see if can initate colonies



Paired daughter cell assays

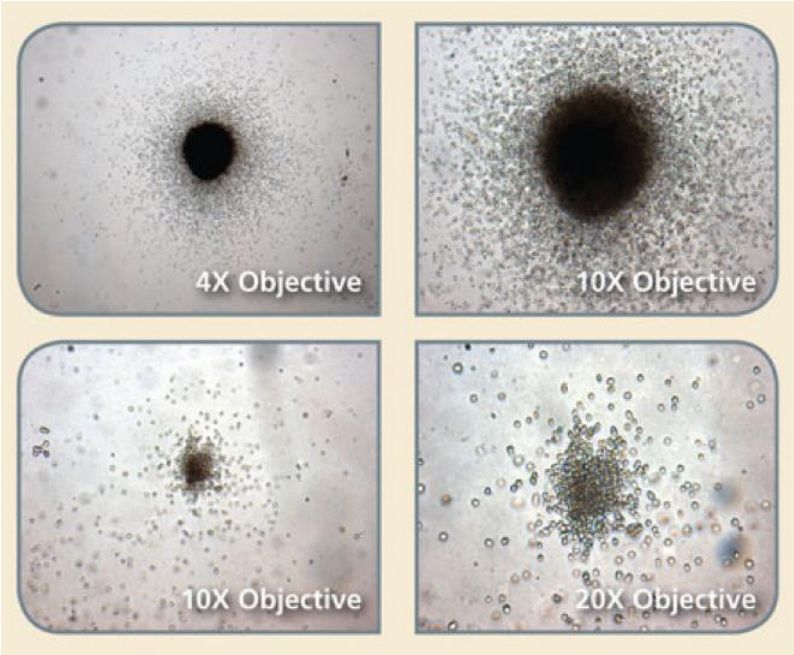
Micromanipulation of progeny following 1st cell division to test symmetric vs asymmetric division



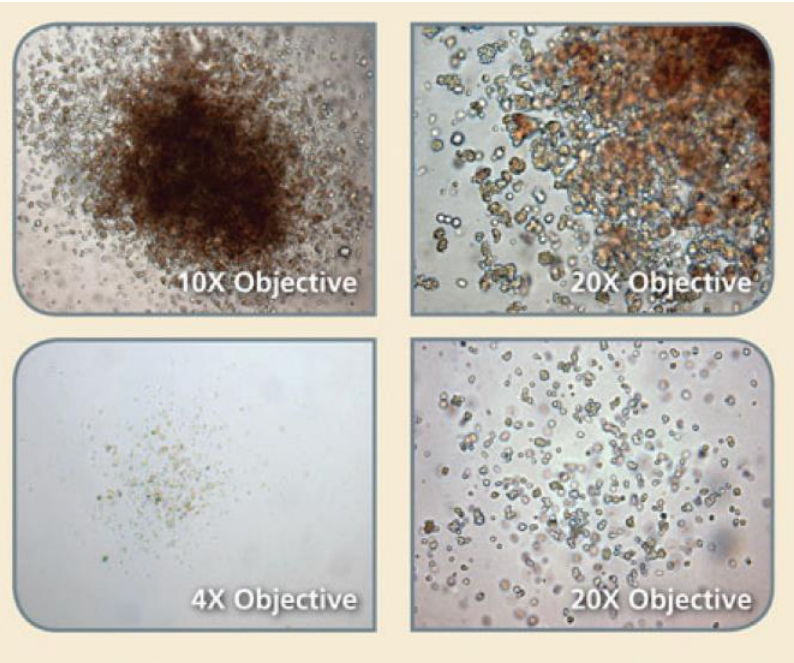
In vitro differentiation assays

Semi-solid ‘clonogenic’ assays: mix cells with methylcellulose (+ cytokines)

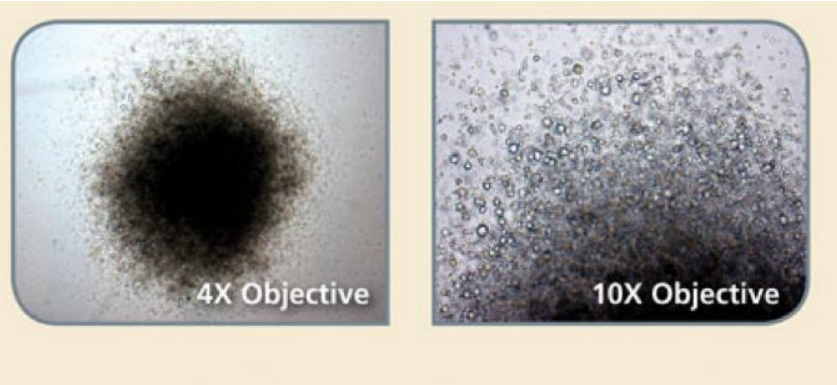
CFU-GM
Ery



BFU-E
Ery

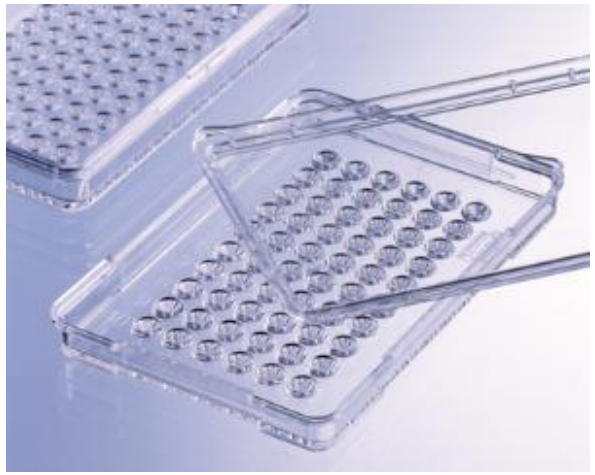


CFU-GEMM
Gran, ery, macrophage, mega



In vitro differentiation assays

- Liquid culture (single cell 96-well plate or Terasaki plates)



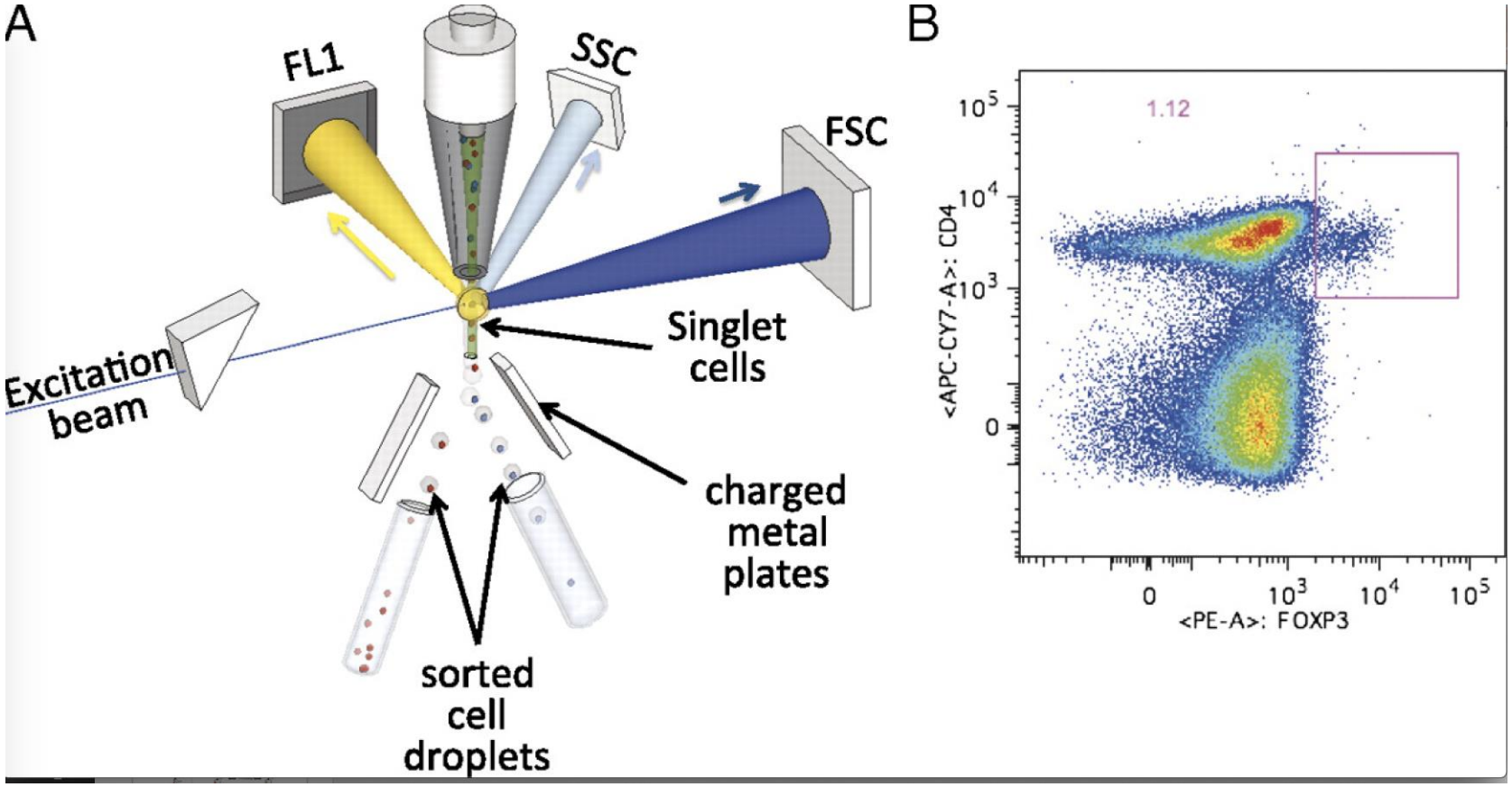
Stemspan (serum free media)
+ Stem cell Factor
+ erythropoietin
+ thrombopoietin
+ G-CSF, GM-CSF
+ Interleukins IL3, 6
+ FLT3-Ligand

May need stromal support cells
- OP9 for B –ells
- OP9DL1 for T cells

Semi-solid / liquid culture pitfalls

- Measure progenitor frequency rather than HSCs
- Assessing multipotency of single cells is really challenging
- Readout is very dependent on skills and experience of observer!
- Biased by culture conditions / cytokines added

Phenotypic assays: immunophenotyping



Cells are excited by laser beams, to delineate forward scatter (FSC) and side scatter (SSC) and labelled with fluorescently-labelled antibodies detected by fluorescent light (FL1)

Jaye et al, J of Immunol 2012

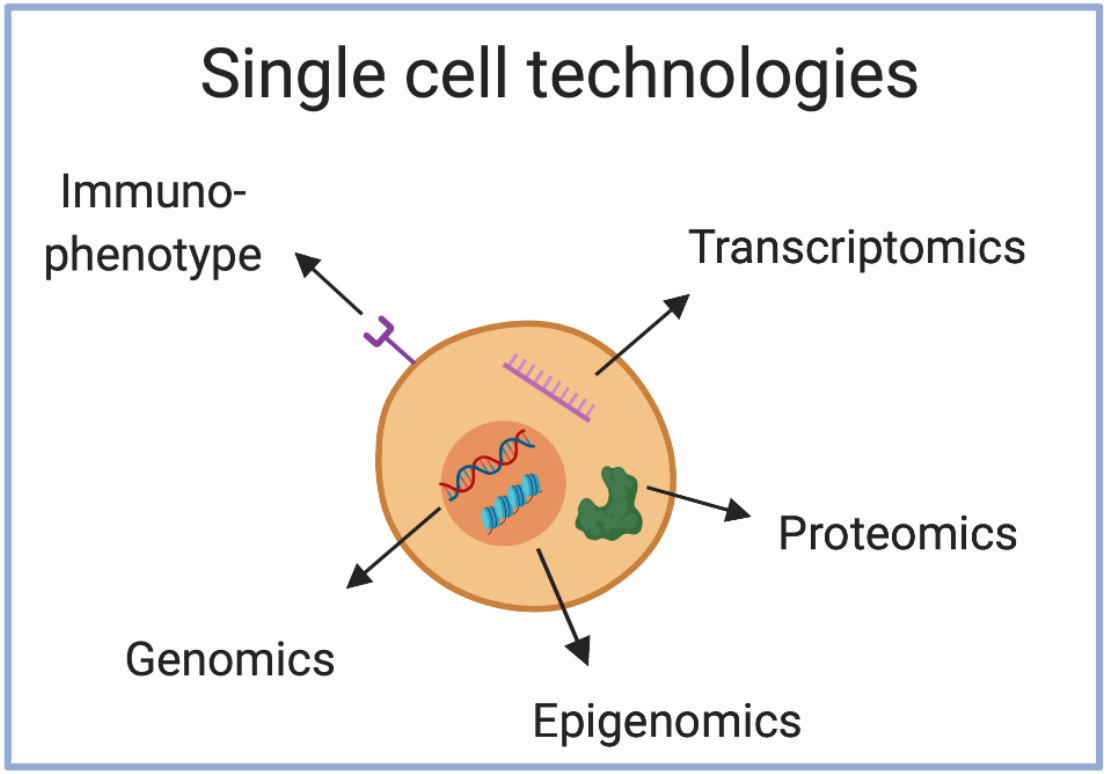
Phenotypic assays: immunophenotyping

- Various different immunophenotyping strategies for mouse and human

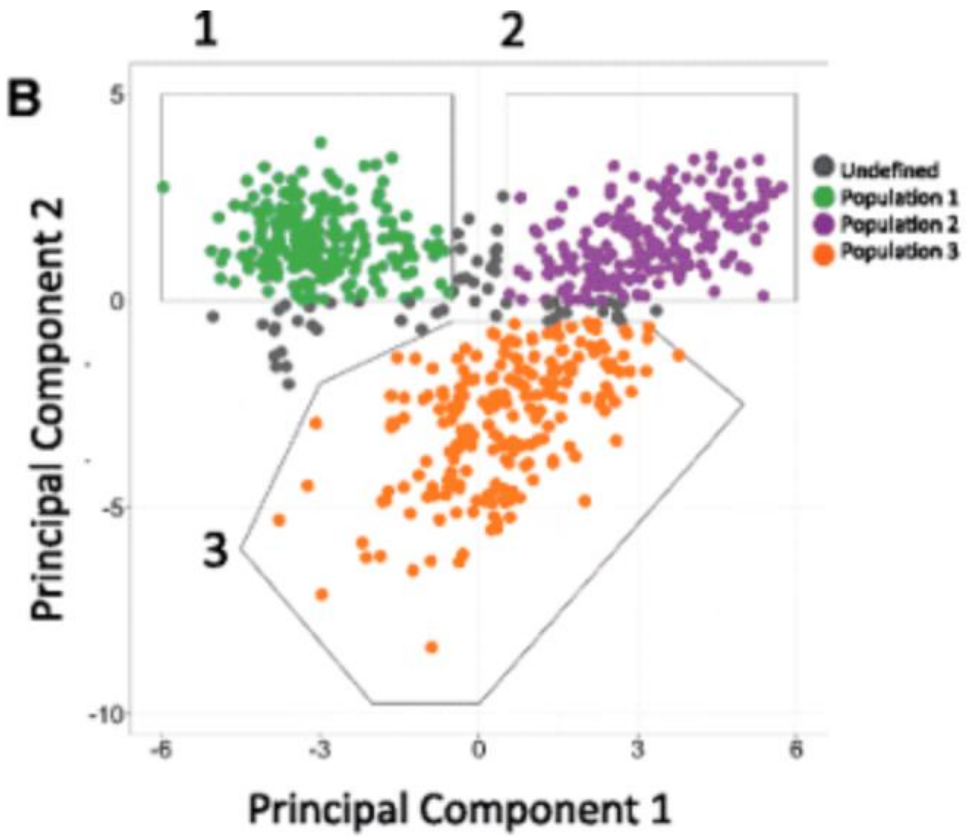
- Purity of HSCs identified using the most state-of-the-art FACS methods is thought to be around 50% (assessed by the transplantation assay)
  - Variability in HSC antigens between different mouse strains
  - Different stages of ontogeny
  - Cell cycle
  - Non-steady state e.g. post transplant/5-FU treatment

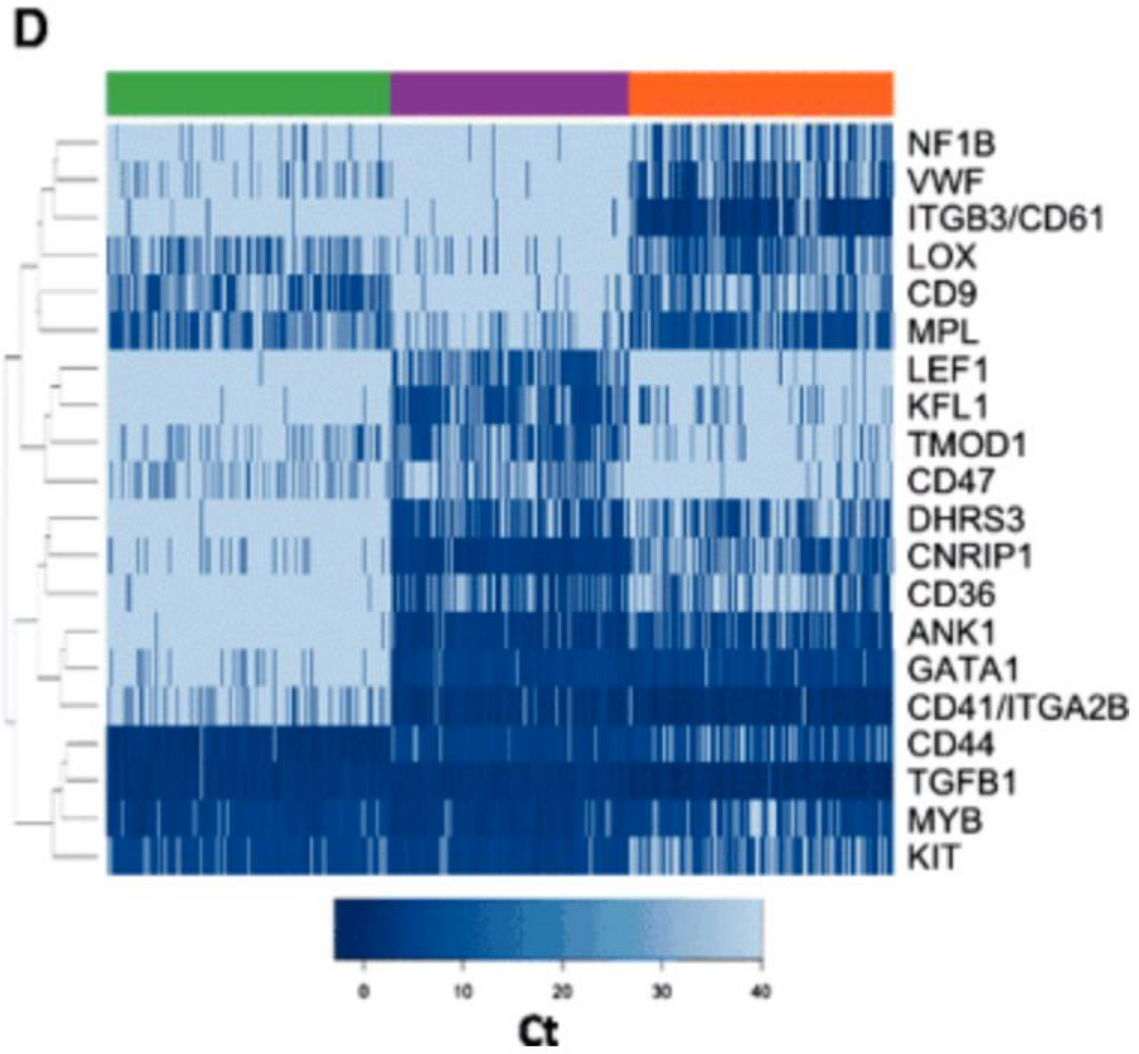
→ ‘true’ HSC need to be defined by functional analyses

Molecular profiling to identify stem/progenitor priming



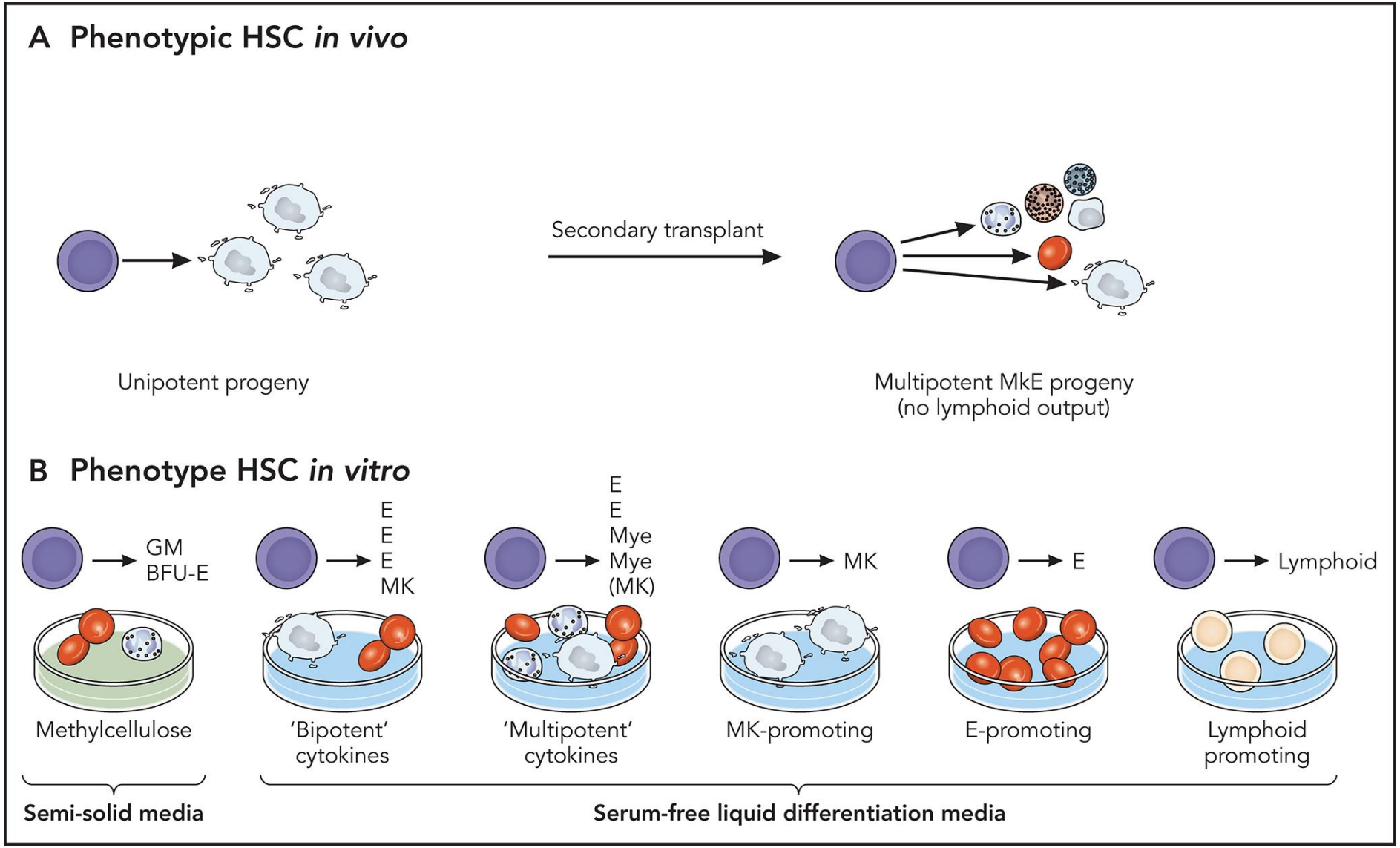
Molecular profiling to identify stem/progenitor priming





Psaila, Genome Biology 2016

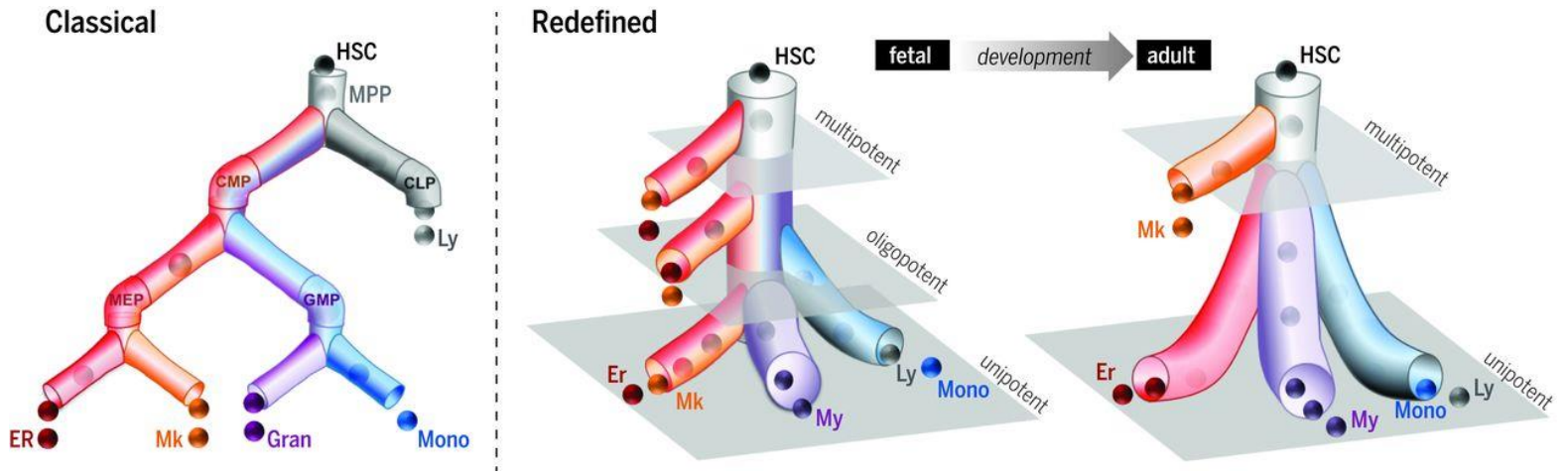
Limitations in stem cells assay even at single cell level



Questions/controversies

- Does haematopoiesis occur via step-wise transitions or over a gradual continuum of differentiation?

- What % of HSCs are truly ‘multipotent’? Recent data suggests that majority of HSCs in adult life are ‘biased’ towards certain differentiation fates



Science
AAAS

Faiyaz Notta et al. Science 2016

Questions/controversies

- Do HSCs contribute to steady-state haematopoiesis or are they a ‘reserve’ (with most contributions coming from progenitors)?

- How much similarity is there between humans and animal models?

Why does this matter?

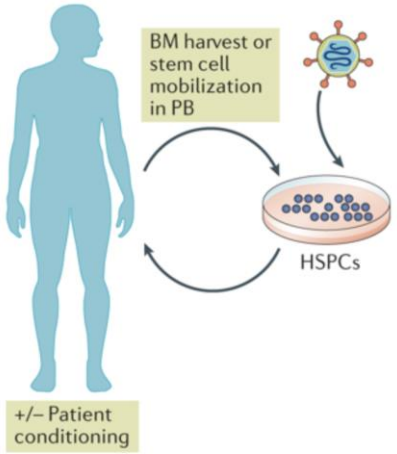
Abnormalities of blood cell production

- **Too few cells produced**
  - Bone marrow failure e.g. aplastic anaemia
  - Anaemia, neutropenia, thrombocytopenia
- Too **many** cells produced
  - Essential thrombocythaemia
  - Polycythaemia vera
  - Chronic myeloid leukaemia
- **Abnormal** cell production
  - Malignant: leukaemia, myelodysplasia
  - Non-malignant: sickle-cell anaemia

What are the potential clinical uses of HSCs?

What are the potential clinical uses of HSCs?

- Transplantation for haematopoeitic disorders e.g. leukaemia
- In vitro production of red cells, platelets
- Repair of damaged tissue e.g. heart, liver
- Gene therapy e.g. SCID, thalassaemia



See review by Cavazzana et al, Nature Reviews 2019

Summary

- Haematopoiesis migrates from YS --> AGM --> FL → FBM in fetal life
- Postnatal life, continues in bone marrow
  - Pathological extramedullary haematopoiesis can occur in liver, spleen, almost anywhere!
- Regulated by key genes and transcription factors
- Regulated by growth factors and the microenvironment
- Review of *in vivo* and *in vitro* experimental techniques and challenges

→ need to carefully evaluate what has been done and what the assay is ***actually*** testing (cell fate vs potential) to interpret the literature

Questions?