



# Ninth AusIMM Open Pit Operators' Conference 2016



*Adapting to Change*

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# **NINTH AUSIMM OPEN PIT OPERATORS' CONFERENCE 2016**

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# Determination of the Transition Point from Open Pit to Underground Mining

J Chung<sup>1</sup>, M Asad<sup>2</sup>, E Topal<sup>3</sup> and A K Ghosh<sup>4</sup>

## ABSTRACT

Many open pit (OP) mines with considerable vertical extent are approaching the end of their life-of-mine; some of them are seeking the opportunity to make the transition from OP to underground (UG) mining. The decision on the best location for transition from OP to UG mining should be addressed at the strategic mine planning stage. Conservatively, the transition to UG mining is considered near or after the exhaustion of the reserve within the ultimate pit.

However, if UG is evident and exclusively viable from the inception, defining the best location for the transition through a conservative approach may not be an optimal option to explore. This clearly establishes the need for a mathematical model that aims to maximise the project value and considers OP and UG mining with crown pillar (CP) requirement simultaneously. Underground mine layout varies from one UG mining method to the other, and consequently the variation in the location of transition is eminent. Thus, focus on the selection of UG mining method must be a part of this analysis

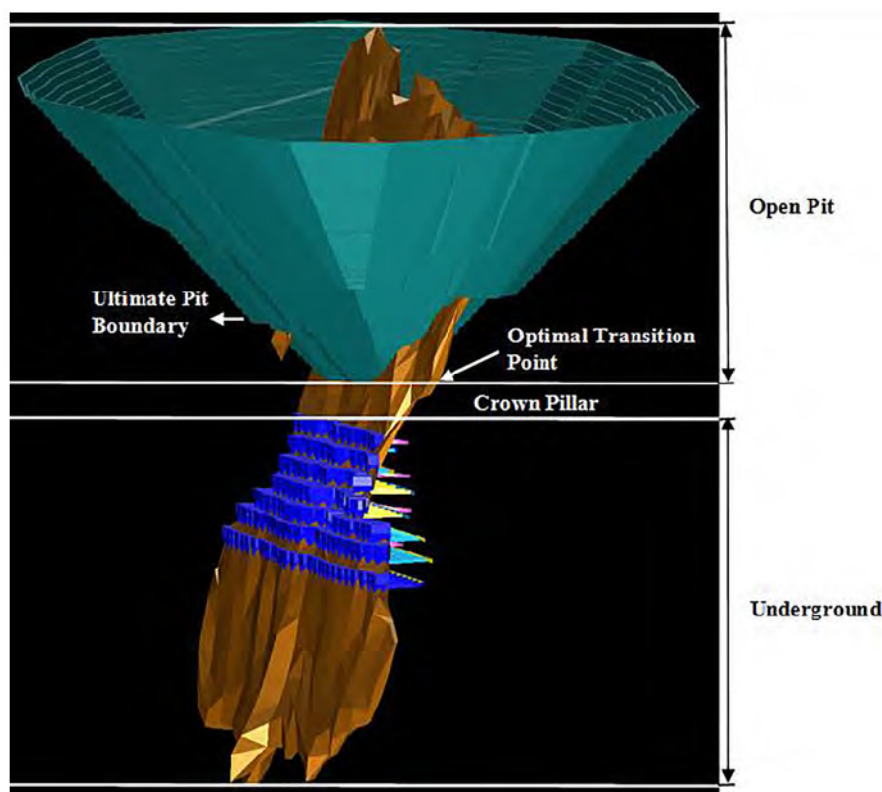
This paper presents an implementation of an integer programming (IP) based mathematical model that evaluates the changes in mining layout and the project value under possible variation in the transition point from OP to UG mining for stoping and block caving methods. An IP problem is a mathematical optimisation or feasibility method in which some or all of the variables are restricted to be integers. The outcome of the implementation reflects that mining strategies with OP transition to stoping and block caving methods generated higher values than OP-only mining strategy. The case study not only demonstrates the difference in mining layout for both stoping method and block caving method, but also reflects that a joint consideration of OP mining, UG mining and CP placement helps to achieve maximum project value and resource utilisation.

## INTRODUCTION

Shallow orebodies are preferably mined through open pit (OP) mining method due to its low cost of extraction. As orebodies extend vertically to a considerable depth, the haulage cost and stripping ratio in OP mining will increase when the pit goes deeper. Consequently, as the OP mining becomes uneconomical, underground (UG) mining emerges as a viable option. The transition from OP to UG mining requires a challenging and strategic decision on the optimal location of the transition point as it can significantly impact the profit generated from a project. Hence, the determination of the optimal transition point and create maximum undiscounted profit is known as transition problem. Figure 1 is a schematic of the transition from OP to UG mining for a typical large-scale steep dipping deposit.

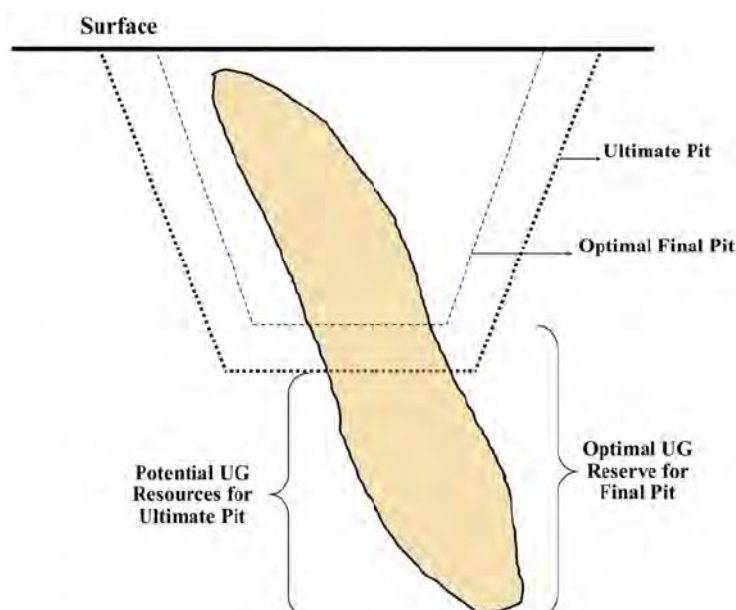
Solving the transition problem is important for combination mining method as it determines the optimal transition point and mining layout. The case of the transition from OP to UG mining is considered near or after the exhaustion of available reserves inside the ultimate pit limit is known

1. GAusIMM, PhD Student, Curtin University (WASM), Bentley WA 6102. Email: joyce.chung@postgrad.curtin.edu.au
2. MAusIMM, Head of Discipline, Curtin University (WASM), Kalgoorlie WA 6430. Email: waqar.asad@curtin.edu.au
3. MAusIMM, Professor, Curtin University (WASM), Bentley WA 6102. Email: e.topal@curtin.edu.au
4. MAusIMM, Lecturer, Curtin University (WASM), Kalgoorlie WA 6430. Email: apurna.ghosh@curtin.edu.au



**FIG 1** – Schematic of transition from open pit to underground mining (Chung, Topal and Erten, 2015).

as conservative method. This may lead to a situation where UG mining could have been the optimal strategy for some of the OP reserves, but were planned for mining through an OP operation; this situation is showed in Figure 2. This methodology evaluates OP and UG mining options separately and ignores the variation in mining layout from one underground mining method to the other. The location of the crown pillar (CP) is critical to the combination mining method and transition problem, as the resource within the CP may not be recovered. The conservative approach defines the CP in an arbitrary location; however, due to the potential for sterilisation of the CP, the CP should be located in a zone that is least valuable for extraction either by OP or UG mining. The CP placement is not considered, unless the OP and UG mining methods are not considered jointly. These limitations in the conservative approach establish the need for optimisation of the transition point and location of



**FIG 2** – Distributions of reserve for open pit and underground mining.



the CP. This should be completed by a technique that simultaneously evaluates OP and UG mining along with a variation in underground mining layout.

There are numerous simplex mathematical models and methodologies available to optimise OP mining and UG mining operations. Some of the notable contributions include Lerchs and Grossman (1964), Johnson (1968), Dimitrakopoulos, Martinez and Ramazan (2007), Topal and Ramazan (2012), Asad and Topal (2011), Brazil *et al* (2005) and Alford (1995). These approaches address the mine planning aspects of the selected OP and UG mining methods. Similarly, there are researches have been carried out to solve the transition problem of combination mining method with the aim to maximise project value. Soderberg and Rausch (1968) presented a break-even cost differential method between two mining methods which emphasised the relationship between mining costs and stripping cost. CP placement was disregarded. Camus (1992) assessed the transition problem by integrating the opportunity cost of the UG mining into the OP economic block model; this approach was innovative but CP placement was again disregarded. Besides, heuristic approach had been suggested by Bakhtavar and Shahriar (2007) which practices Korabov algorithm for pit optimisation and subdivide the final pit level to compare with the UG's value; this approach did not generate optimal result due to the nature of the methodology. Bakhtavar, Shahriar and Mirhassani (2012) introduced binary integer programming to handle the transition problem; however, the mathematical model needs to take further improvement to ensure its practicality. Opoku and Musingwini (2013) recommended a structured approach to guide the decision-making process by introducing transition indicator. This approach heavily depended on the predetermined transition indicator. Dagdelen and Traore (2014) introduced an iterative approach to solve the transition problem but it failed to generate an optimal result and it assumed that transition will only happened after the ultimate pit limit. However, none of these studies achieved an optimal strategic plan, where OP and UG mine plans, underground mine layout and placement of the CP are considered simultaneously. Given these gaps in existing literature, the objective of this study is to present an implementation of an integer programming (IP)-based mathematical model that evaluates possible variations in transition point from OP to UG mining for sublevel stoping and block caving methods; and to demonstrate the impact of OP and UG mining strategies and different underground mining methods on the layout of underground operations, as well as overall value of the project.

## MATHEMATICAL MODELLING FOR OPTIMAL TRANSITION

In this research, the determination of the optimal transition point is accomplished through an implementation of an IP model given in Chung, Topal and Ghosh (2016). The general setting of an IP model consists of an objective function and a set of constraints. A summary of the models for both sublevel stoping and block caving methods are presented as follows.

*Objective function:* maximises the undiscounted profit from both OP mining  $\sum_{i \in M_i} C_i x_i$  and UG mining  $\sum_{j \in N_j} S_j y_j$

where:

- $i$  is the block indicator for OP mining
- $j$  is the stope indicator for UG mining
- $C_i$  is the expected undiscounted profit from block  $i$
- $S_j$  is the expected undiscounted profit from stope  $j$
- $M_i$  is the set of all blocks in the block model for open pit mining
- $N_j$  is the set of all possible stopes in the block model for underground mining

Also, the binary decision variables  $x_i$  take either a value equals to 1 or 0, ie if  $x_i$  is equal to 1, then block  $i$  is mined through OP, and if it is equal to 0, then block  $i$  is not mined through OP mining. A similar explanation applies to the variable  $y_j$ .

*Constraints:* the model satisfies:

- OP slope or block precedence constraint that requires the removal of all overlying blocks for mining a candidate underlying block
- UG stope design constraints that force the stope to be discrete and not overlapped to other stopes
- the reserve constraint that ensures each row/level can only be mined either by OP, UG or positioned as CP

- CP location and design constraint that ensures the placement of CP is underneath the pit
- the provision of required number of levels needed for CP is in accordance to the geotechnical requirement.

The IP model which can be used to determine the optimal transition point for the transition from OP to UG block caving mining system is summarised as follows.

*Objective function:* maximises the undiscounted profit from both OP mining  $\sum_{i \in B} C_i x_i$  and UG mining  $\sum_{j \in D} C_j y_j$

where:

- $i$  is the block indicator for OP mining
- $j$  is the block indicator for UG mining
- $C_i$  is the expected undiscounted profit from block  $i$
- $C_j$  is the expected undiscounted profit from block  $j$
- $B$  is the set of all blocks in the block model for OP mining
- $D$  is the set of all block in the block model for underground mining

Also, the binary decision variables  $x_i$  and  $y_j$  take either a value equals to 1 or 0, ie if  $x_i$  is equal to 1, then block  $i$  is mined through OP, and if it is equal to 0, then block  $i$  is not mined through OP mining. A similar explanation applies to the variable  $y_j$ .

*Constraints:* the model satisfies:

- OP slope or block precedence constraint that requires the removal of all overlying blocks for mining a candidate underlying block
- UG mine design constraints that force the vertical continuity and same level drawpoint placement
- reserve restriction constraints that ensure each row/level can only be mined either by OP, UG or retained as CP
- CP design constraint that ensures the placement of CP is underneath the pit
- the provision of required number of level needed for CP is in accordance to the geotechnical requirement.

## UNDERGROUND MINING METHOD

UG mining method is not preferred for shallow deposit due to high mining cost, low production rate, safety perspective and intensity of the development cost. However, when the pit goes deeper, the cost of haulage for OP mining escalates drastically. Therefore, as the OP mining cost increases, the relative cost of UG mining methods decreases, an UG mining method will thus generate a higher project value and UG mining method emerges as preferred option.

This paper implements the IP model, in the context of block caving and sublevel stoping UG mining methods. Table 1 shows the application criteria and economic comparison between these two methods. Also, it needs to be aware of that the technical and other limitations in the application of combination mining method with transition from OP to UG mining could be different in terms of production rate, equipment requirements and variation of labour skills after transition. Bulk mining methods are one of the preferred options in the context of production rate and mining cost; block caving would be an ideal UG mining method for combination mining method. Block caving method depends on the cave-ability of the ore and host rock; therefore, it can only be applied to the deposits that are suitable for caving. However, there are a number of technical issues for block caving method

**TABLE 1**  
Underground stoping and block caving mining methods application criteria.

Mining method	Ore geology	Economics
Block caving	Low-grade and dilution compensated by vast throughput	Potentially the lowest mining cost per tonne and highest underground production rates. Can be very expensive if caving cannot be maintained.
Sublevel stoping	Low-grades, high tonnages	Minimum waste dilution if hanging wall is strong. Relatively low cost, small workforce, steady production from drawpoints. Stopes can be filled with waste rock, paste fill to aid pillar extraction.



such as cave propagation, recovery and long lead time prior to production which will lead to higher cost incurred. The intensive development cost of block caving mining method also a deficiency of the method. Sublevel stoping is one of the most popular UG mining methods as it is flexible to handle variations in mine design and uncertainties in orebody. It has relatively low mining cost, but it will generate a slightly higher cost than block caving mining method. The possibility of early production and relatively lower development cost than block caving makes the method advantageous.

## CASE STUDY AND RESULT DISCUSSIONS

The basic input to the mathematical model is a block model that represents a hypothetical gold deposit. The block model is constituted of blocks at a block size of  $25\text{ m} \times 25\text{ m} \times 25\text{ m}$ . Figure 3 shows the grade distribution within this block model. Upon the completion of the OP mining, at least two and three levels will be retained as crown pillar for sublevel stoping mining method and block caving mining method respectively. Similarly, for sublevel stoping method, the stope size is restricted to  $2 \times 2 \times 2\text{ blocks}$ . Besides, the assumed costs which have been used in this case study is demonstrated in Table 2. Given these assumed inputs, this study explores the following five scenarios:

1. OP – UG stoping method
2. OP – UG block caving method
3. OP mining method only
4. UG stoping method only
5. UG block caving only.

As part of the optimisation process, a computer program in VB.NET develops the IP formulation, which is then solved on a standard IC i7 3.40 GHz CPU and 8 GB RAM machine using IBM CPLEX Optimisation Solver (Version 12.6 IBM CPLEX ILOG Corp 2013). Table 3 presents the problem size in the context of the number of binary (0/1) variables in the IP formulation.

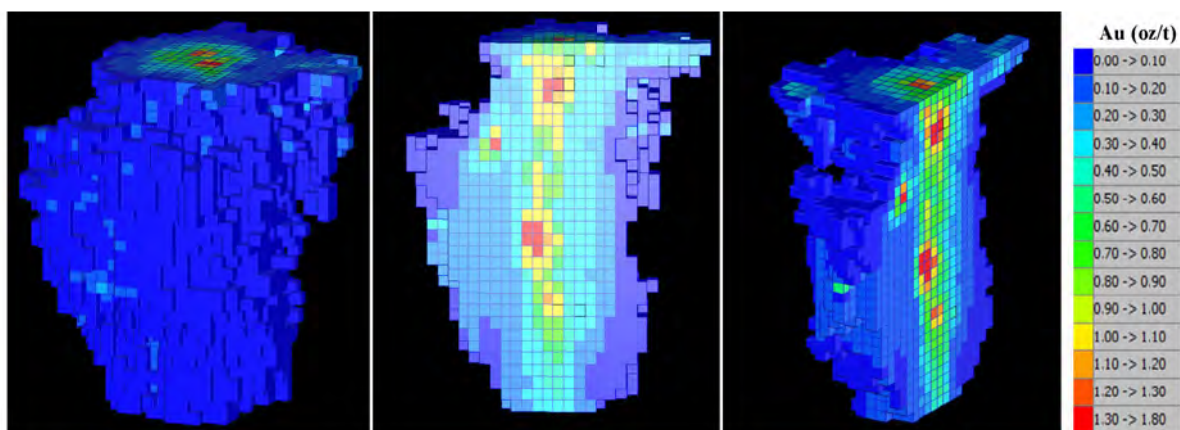


FIG 3 – Resource model for the hypothetical gold deposit.

TABLE 2  
Assumed costs.

Parameter	Cost \$
Metal price	860 oz
Processing cost	20/t
Open pit mining cost	0.5/t
Additional open pit mining cost from bench below 9975 m	0.1/t
Underground mining cost – stoping method	50/t
Underground mining cost – block caving method	1.25/t

**TABLE 3**  
Problem size definition.

Components	Model information	
<b>Block model size</b>	<b>41 472</b>	
Problem size (stopping method)	Open pit blocks	41 472
	Underground blocks	4051
	Binary variables	45 619
Problem size (block caving method)	Open pit blocks	41 472
	Underground blocks	41 472
	Binary variables	83 040
Problem size (open pit mining only method)	Open pit blocks	41 472
	Underground blocks	0
	Binary variables	41 472
Problem size (underground stopping only method)	Open pit blocks	0
	Underground blocks	622
	Binary variables	622
Problem size (underground block caving only method)	Open pit blocks	0
	Underground blocks	41 472
	Binary variables	41 536

## RESULT DISCUSSIONS

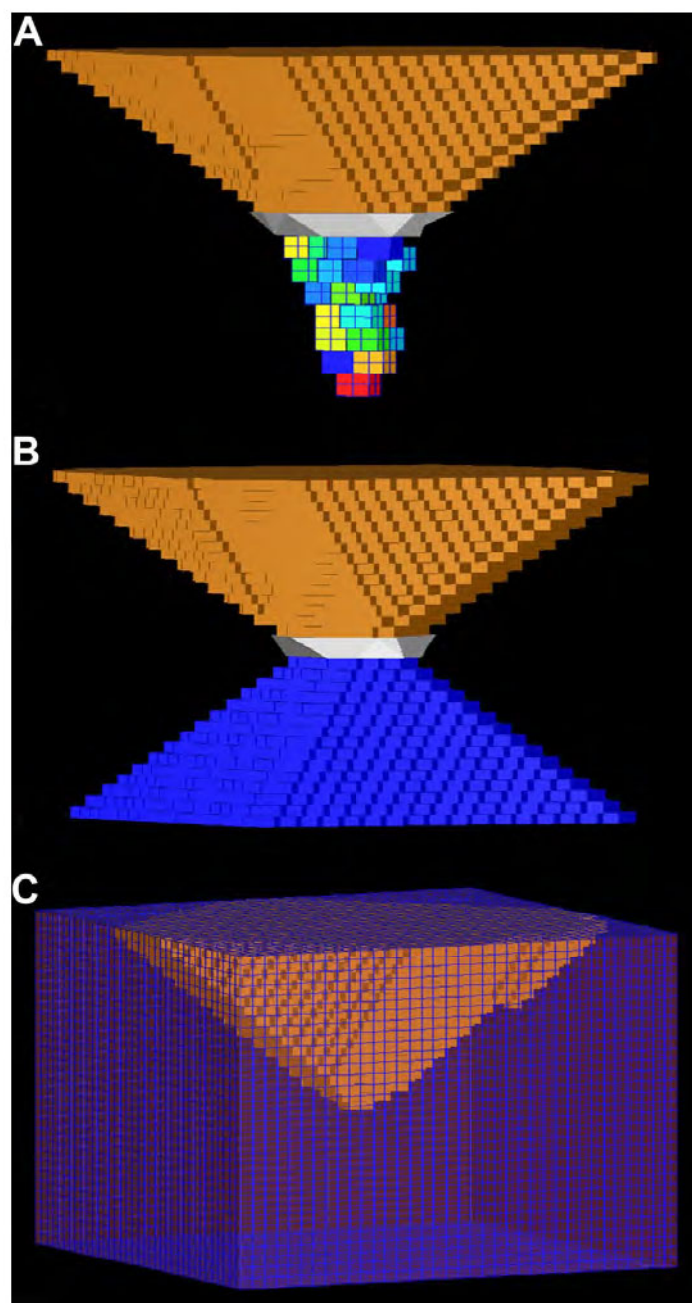
Table 3 presents a summary of the results generated from the IP formulation. As can be seen from the results in Table 4, in the case of a shallow deposit with large vertical extent, combination of OP and UG mining turned out to be the most suitable mining method, as scenarios 1 and 2 gave the highest values among all scenarios. Similarly, a combination of OP and UG mining with block caving option generated a the higher project value compared to scenario 1, and this project value difference is mainly due to relatively low mining cost coupled with high production rate and economy of scale. Moreover, the combined OP mining and UG stopping method gave a higher value than OP mining method only, which leads us to the argument that if the deposit can be mined through a combination of OP and UG mining methods, optimality can be achieved through strategic mine planning considering OP, UG and CP concurrently.

Furthermore, in the result generated, as the CP location for scenario 1 is at Levels 17–18 (9900–9950 m) and scenario 2 is at Levels 16–17 (9875–9925 m), respectively.

Figure 4 presents the 3D view of the results derived from the IP model. Again, the difference in the layout of the UG operation from scenario 1 to scenario 3 is obvious in Figure 4. The results demonstrate if OP mining is selected for the shallow deposit without considering the potential transition to UG mining, the ultimate pit will extend deeper than the final pit generated by the combination mining method. However, in the perspective of optimisation, there are some blocks or portions in the block model that will generate a better value if being mined through an UG mining

**TABLE 4**  
Results generated by integer programming model.

Scenarios	Integer programming model results (\$billion)
Scenario 1: open pit – underground stopping method	21.657
Scenario 2: open pit – underground block caving method	26.020
Scenario 3: open pit mining method only	18.396
Scenario 4: underground stopping method only	12.541
Scenario 5: underground block caving method only	13.123



**FIG 4** – The mining layout of (A) scenario 1; (B) scenario 2; (C) scenario 3.

method instead of OP mining method. Therefore, a realistic analysis should consider both OP and UG mining methods simultaneously to achieve an optimal mining strategy. Not only this will help include the opportunity cost of all available mining strategies, but will also help avoid the delays in production during the transition from OP to UG mining.

The results derived from the IP model reflect the significant of planning the transition from OP to UG mining strategically for deposit extend vertically to a depth. The project value with deposit extend vertically to a depth could be improved by reducing extra waste handling in OP mining and make the transition to appropriate UG mining method. The resource and reserve utilisation could be maximised by accessing the reserves that would otherwise remain in ground.

## CONCLUSION

The results of the model clearly demonstrate the importance of considering both OP and UG concurrently during the strategic mine planning process. As opposed to the conservative approach that only considers OP and UG mining separately, a joint consideration of both in the early stages of the strategic mine planning process leads to the optimal value of the project as well as the mining



layout. In this context, UG mining method selection plays an important role, in which orebody and geotechnical characteristics of the deposit determine the appropriate UG mining method.

As part of the implementation, a 3D hypothetical block model was created to evaluate five different scenarios; the results show that a combination of OP and UG block caving method generates the highest value with the existing economic and geological inputs. The results show that with the existing economic and geological inputs, combination mining methods generate the highest values; the combined of OP and UG block caving method generates higher value than the combined of OP and UG stoping method.

The proposed IP model is still in its infancy. Its framework of the IP model proposed in this paper is limited, and hence, further enhancement required. The future study will be focused in problem size reduction, determination of transition period and the impact of development cost. Besides, fluctuation of economic parameters and geological uncertainties of the project will also affects the transition point which has been demonstrated by Chung, Topal and Erten (2015). Hence, the uncertainties involved in a project will require to be focused in the future research scope.

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